Omega-P, Inc.

199 Whitney Avenue, Suite 200
New Haven, CT 06511

Final Report to US Department of Energy
on

Phase I SBIR Grant DE-FG02-04ER84029

120 MW, 800 MHz MAGNICON FOR A FUTURE MUON COLLIDER

Principal Investigator: J. L. Hirshfield
December, 2005

TABLE OF CONTENTS

1. Identification and significance of the problem or opportunity, and technical approach	p. 2
1a. Introduction	2
1b. Technical approach	2
2. Anticipated public benefits	4
3. Degree to which Phase I has demonstrated technical feasibility	6
3a. Electron gun design	6
3b. Magnetic system design	10
3c. Magnicon RF cavity designs	11
3d. Beam dynamics optimization	16
3e. Beam collector	18
3f. Summary of results of Phase I study	21
<i>References</i>	22

1. SIGNIFICANCE, BACKGROUND INFORMATION, AND TECHNICAL APPROACH

1a. Introduction

Under Topic 6d in the DoE 2004 SBIR Program Solicitation *Radio Frequency Power for Muon Colliders*, Phase I proposals were sought for "...new concepts, approaches, or designs for radio frequency amplifiers...for use in the acceleration and ionization cooling channels of a future muon collider.... Higher power (>100 MW) pulsed sources at higher frequencies (from 30 microseconds at 400 MHz to 10 microseconds at 800 MHz) are also of interest. All muon collider amplifiers must have moderate repetition rate capability (e.g., 15 Hz)." In response Omega-P, Inc. submitted a proposal, and was awarded Phase I grant DE-FG02-04-ER 84029 entitled "120 MW, 800 MHz Magnicon for a Future Muon Collider." The overall goal of the R&D program that was started in Phase I included the design of a magnicon amplifier at 800 MHz with a peak power output of more than 100 MW that would be suitable for a future muon collider. This Final Report describes results obtained by Omega-P during Phase I that resulted in design improvements and strengthened confidence in the original concept, thereby justifying a proposal for continuation of Phase I into Phase II. The Phase II proposal was not approved.

1b. Technical Approach

The magnicon [1] is a microwave amplifier tube that combines the scanning-beam synchronism of the gyrocon [2] with a cyclotron resonant, fast-wave interaction in the output cavity. The transverse momentum that drives the output cavity interaction is generated in a series of deflection cavities all operating in synchronously rotating TM_{110} modes. The input cavity acts upon a small diameter solid electron beam, where rotating RF fields of an externally-driven TM_{110} mode convert a small fraction of the beam axial momentum into transverse momentum (Larmor motion), directed across the applied axial dc magnetic field. The beam then transits a sequence of gain cavities, where the transverse beam momentum induces amplified RF fields that further deflect the beam, producing a progressively higher fraction of transverse momentum. The RF fields in each of the deflection cavities rotate synchronously with the externally-driven RF fields of the drive cavity. Unlike the gain cavities of a klystron, those of the magnicon are not used to create bunching, but rather to amplify the transverse motion of the beam. Because all of the cavities contain synchronously rotating modes, electron motion is synchronous with the phase of the RF fields in each of the deflection cavities. 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 drives a cyclotron-resonant, fast-wave interaction with a synchronously rotating TM_{m10} mode, at the m^{th} harmonic of the drive frequency, which extracts power principally by reducing the transverse beam momentum. In order to obtain high efficiency, electrons should have $\alpha \geq 1$ at the entrance of the output cavity, where α is the ratio of transverse to longitudinal momentum.

Different versions of magnicons have been built from the decimeter to the millimeter wavelength domains, operating in the first, second, and third harmonic modes. The first magnicon was built and tested in 1985 in Novosibirsk [3]. A power of 2.6 MW was obtained at 915 MHz with a pulse length of 30 μsec and electronic efficiency of 85%. That tube is a first (i.e., fundamental) harmonic amplifier. This device was successfully tested not only with

absorbing loads, but with a resonant accelerating structure as well [4]. This success led to projects for development of magnicons at wavelengths from decimeter to millimeter ranges for different accelerator projects. As a prototype of a microwave power source for linear collider applications, a second magnicon concept was also developed in Novosibirsk. The magnicon tube developed for this application is a frequency doubler, or second harmonic amplifier, operating at a frequency of 7 GHz [5,6]. This magnicon has demonstrated experimentally an output power of 55 MW, an efficiency of 56%, and a gain of ~70 dB in a 1 μ sec pulses, in very good agreement with simulation results [7,8]. Another frequency-doubling magnicon amplifier at the NLC frequency of 11.424 GHz has been designed and built in a collaboration between Omega-P, Inc and Naval Research Laboratory (NRL). The tube is designed to produce ~60 MW at 60% efficiency and 59 dB gain, using a 470 kV, 220 A, 2 mm-diameter beam. At present, the tube is conditioned up to power level of 25 MW for 0.2 μ sec pulse widths [9]. The power is limited by the oscillations in the beam collector [9]. Construction of the new collector is under way at present. Operation of this latter magnicon has established a research facility located at NRL as only the second laboratory in the USA, after SLAC, where high-power microwave development at the NLC X-band frequency can take place. A high power third-harmonic magnicon at 34.272 GHz has also been designed and built as a microwave source to develop RF technology for future multi-TeV electron-positron linear colliders. After preliminary RF conditioning, this tube produced an output power of >10 MW in 0.25 μ s pulses, with a gain of 54 dB [10]. These preliminary results already constitute record values for a millimeter-wave accelerator-class amplifier.

The interaction mechanism of the magnicon does not require beam bunching, and consequently does not require long drift spaces between the RF cavities. As a result, the RF system of a magnicon can be substantially shorter than the RF systems of either SBK's or MBK's. This advantage is especially significant at high powers, as required for a muon collider.

To illustrate the differences between these types of RF sources, comparison is presented in Table I of an SBK, an MBK and a magnicon, all at 800 MHz with powers of 120 MW. The parameters of the SBK are obtained by scaling of existing SLAC klystrons having powers of 75 MW and 150 MW [11,12]. The MBK parameters are obtained by scaling from Thales tubes with powers of 10 MW and 47 MW [13,14]. The magnicon parameters are from the innovative preliminary design presented in this proposal. From Table I one can see that the SBK simply has unreasonable length. The MBK is still too long, and besides, its scaling was made with assumptions taken from the design example of the future CERN MBK with a power of 47 MW [14], where the beam area compression ratio is taken to be 5.6:1; however, this is in contradiction with the current state-of-the-art for MBK guns [15], where the compression does not exceed 2:1. The required current density of 9 A/cm² for the MBK is also somewhat on the high side.

Table I. Lengths of RF systems for different 120 MW, 800 MHz rf amplifiers.

type of RF amplifier	beam voltage (kV)	beam current (A)	length of rf system (m)	reference used for scaling
SBK	550	400	8.5	[11,12]
MBK	300	600	4.5	[13,14]
magnicon	550	360	2.5	this proposal

In addition to a most critical issue of tube dimensions, magnicons can protect themselves to a greater degree than klystrons against tube damage when an arc occurs in the RF circuit. Should an arc occur somewhere in the RF circuit, a pulse with peak power exceeding the output of a tube could be directed back towards the tube. This could cause damage to the tube's output window. It might also decelerate the beam sufficiently to cause it to reflect back towards the gun and possibly damage the rf structure or cathode. This latter scenario should not occur in a magnicon, since RF fields in magnicon cavities cannot totally decelerate the beam longitudinally, a point that has been checked both in simulations and experiments [1,3,4]. This fundamental feature of the magnicon can provide a margin of insurance against tube damage not enjoyed by the klystron.

2. ANTICIPATED PUBLIC BENEFITS

Advancement in high-energy physics has, in the years since WWII, brought enormous practical benefit to the US public in general, and to the US scientific community in particular. Widely-dispersed benefits include fast integrated-circuit electronics, accelerators for radiotherapy and industrial processing, nuclear power, and the internet. For the scientific community, achievements include many discoveries on the fundamental nature of matter and on the origin of the universe. But vexing questions persist, including the nature of dark matter, the origin of mass, extra dimensions, and need "...to illuminate the pathway to the underlying simplicity of the universe.*" Efforts have been carried out by large international research groups that include many scientists trained in the US, using facilities built and operated in the US, thus evincing great pride and prestige among Americans. This positive climate attracted many of brightest young Americans and foreign scholars to high-energy physics and created a scientific work force in the US that is envied and emulated by advanced societies the world over. The curtain on this era in the US could be falling as other countries may be taking the lead in high-energy physics, including the European Community that is now building LHC at CERN in Geneva (with partial US support, it should be said). The international high-energy physics community has pronounced a TeV-scale lepton collider ILC as the next step in its search for a fundamental understanding of Nature. In August 2004, ICFA recommended that, for ILC, a superconducting collider should be built at an initial c-o-m energy of 0.5 TeV, with a possible future upgrade to 0.8 TeV. The competing US/Japan design NLC/GLC that came in behind the superconducting option, in ICFA's view, embodies a room-temperature pair of 10-km microwave-driven linacs, that would be designed to also reach a c-o-m energy of 0.5 TeV, but with possible future upgrade to 1.5 TeV.

So how will the physicist's irrepressible motivation—along with the public's inevitable curiosity—to understand Nature at energies well above 0.8 TeV be satisfied? The motivation for considering muon colliders is their potential high energy reach, together with the fact that muons unlike electrons, generate negligible synchrotron radiation. As a result, a muon collider can be circular and much smaller than the current designs of linear electron/positron colliders, and also much smaller than a hadron machine with the same effective energy. For example, a muon collider with a c.o.m. energy of 3 TeV has a circumference of only 6 km. In addition, a $\mu^+\mu^-$ collider would have unique physics advantages over an e^+e^- collider, as follows:

*R. L. Orbach, in oral testimony before the US House Committee on Appropriations, 3/15/05.

- The direct coupling of a lepton-lepton system to a Higgs boson has a cross section that is proportional to the square of the mass of the lepton. As a result, the cross section for direct Higgs production from the $\mu^+\mu^-$ system is 40,000 times that of an e^+e^- system.

- Because of the lack of beamstrahlung, a $\mu^+\mu^-$ collider can be operated with a small energy spread, that makes possible precision measurements of masses and direct measurements of the Higgs width, that would be otherwise impossible with an e^+e^- collider

Yet, despite huge advances over the past decade, technical limitations still prevent design and operation of a room-temperature microwave-driven electron linac at an acceleration gradient of ~ 100 MeV/m as initially hoped for, but rather closer to 60 MeV/m. Acceleration gradients in the superconducting accelerator prototype TESLA are limited to about 40 MeV/m, due to the inability of superconducting materials to sustain high rf surface magnetic fields. So the goal of building a lepton collider within the foreseeable future that could reach beyond 1 TeV seems somewhat out of reach, if the basis would be existing technology. For this reason, and others given on p. 3, a segment of the accelerator community has fashioned on the concept of instead (or later) building a muon collider. It would be considerably smaller (a ~ 6 km, 3-TeV circular machine, vs a 30-km, 0.5 – 1.0 TeV linear structure). The 120 MW, 800 MHz magnicon amplifier, design of which is proposed here, is one of the most critical technological elements needed for realization of a muon collider. It would evidently be able to satisfy technical specifications otherwise only available from a klystron of much greater size and cost. Thus public benefit from successful completion of the proposed SBIR project would be the enabling of progress in the US towards a goal of again leading the international scientific community towards new and productive research frontiers, with potential of untold benefits to both science and society.

3. DEGREE TO WHICH PHASE I HAS DEMONSTRATED TECHNICAL FEASIBILITY

Efforts towards fulfilling the goals of the Phase I study by carrying out the tasks listed in the Phase I proposal are described in this section. The main design parameters of a 120 MW, 800 MHz magnicon that resulted from work conducted during Phase I are listed in Table II.

Table II. Design parameters of 120 MW, 800 MHz magnicon amplifier.

operating frequency, GHz	800
output power, MW	120
pulse duration, μsec	10
repetition rate, Hz	15
efficiency, %	60
gain, dB	57
bandwidth at -3 dB level, MHz	1.3
beam voltage, kV	550
beam current, A	363
magnetic field in deflecting system, Gauss	800
magnetic field in the output cavity, Gauss	500

3a. Electron gun design.

The 800 MHz, 120 MW tube for the muon collider application should operate with a pulse duration of 10 μsec . For this relatively short pulse width a diode gun may be used, as stated in the Phase I proposal. However, a double-gap (double-anode) gun is more compact, having a smaller anode chamber than a diode gun. In addition, a double-anode gun allows a longer pulse width, that may be useful for other future applications where 100 MW pulse power tubes are required. For example, the muon collider also requires tubes with a power of 100 MW at lower frequency (400 MHz) operating with a pulse width of 30 μsec [16]. The CLIC drive linac requires pulse RF amplifiers with a power of 50 - 100 MW at 937.5 MHz, operating with a pulse width of 100 μsec [14]. Decimeter wavelength magnicons considered for both the muon collider and the CLIC drive linac [17] require similar beam parameters. Thus, a gun with a beam power of 100 MW pulse power capable of operation at a pulse width up to 100 μsec will be suitable for tubes for both a muon collider and the CLIC drive linac.

Due to this long pulse, the electric field in the gun must be relatively low. For pulse lengths shorter than about 1.0 millisecond, an empirical relation [18] for the high voltage breakdown condition is given by $E_s V \leq 100 \tau^{-0.34}$, where E_s is surface electric field on the focus electrode in kV/mm, V is the beam voltage in kV, and τ is pulse width in sec. For $\tau = 100 \mu\text{sec}$ the product $E_s V$ should be less than 2300 kV^2/mm . This requirement represents a challenge in the gun design which can be overcome by using a multi-gap (multi-anode) gun concept. In principle this approach is proven to work well in all Van de Graaff high-voltage accelerators (see e.g. [23]). In the proposed magnicon, the beam parameters are: beam voltage of 550 kV and beam current of 363 A. To provide these parameters with a pulse-width up to 100 μsec , a double-anode gun with a spherical cathode 10 cm in diameter has been designed. Its layout is shown in Fig. 1, where equipotential lines and beam particle trajectories are also shown.

Fig. 1. The double-anode gun layout, trajectories and equipotential lines.

The surface electric fields along the surface of the gun electrodes in both gaps are shown in Figs. 2 and 3. One can see, that $E_s = 82 \text{ kV/cm}$ on the focus electrode and $E_s V_e = 2050 \text{ kV}^2/\text{mm}$ between the first anode and the focus electrode. On the first anode $E_s = 68 \text{ kV/cm}$ and $E_s V_e = 2040 \text{ kV}^2/\text{mm}$ between the two anodes. These values are comfortably below the breakdown limit for a pulse width up to $100 \mu\text{sec}$.

The current density distribution from the center out along the cathode surface is shown in Fig. 4. The maximum cathode loading does not exceed 6.6 A/cm^2 , which allows one to expect a cathode longevity in the range of 40,000 - 50,000 hours according to [19]. (See Fig. 5).

The gun design parameters are listed in Table III

Fig. 2. Surface electric field distribution along the focusing electrode (1st gap) between locations A and B. (See Fig. 1 for identification of these locations.)

Fig. 3. Electric field distribution along the focusing electrode (2^d gap) between locations C and D.
(See Fig. 1 for identification of these locations.)

Fig. 4. Current density distribution along the cathode surface;
 $L=0$ corresponds to the cathode center.

Fig. 5. Semi-empirical curve showing dispenser cathode life prediction *versus* cathode loading [19].

Table III. Design parameters of the electron gun for a 120 MW, 800 MHz magnicon.

beam voltage, kV	550
beam current, A	363
beam power, MW	200
beam perveance, A/V ^{3/2}	0.89×10 ⁻⁶
pulse duration, μsec	up to 100
cathode diameter, mm	100
maximum cathode loading, A/cm ²	6.6
number of anodes	2
voltage V_1 between the cathode and the 1 st anode, kV	250
maximum electric field E_{s1} on the focus electrode (the 1 st gap), kV/cm	82
$E_{s1} \cdot V_1$ (the 1 st gap), kV ² /mm	2050
voltage V_2 between the 1 st anode and 2 ^d anode, kV	300
maximum electric field E_{s2} on the 1 st anode (the 2 ^d gap), kV/cm	68
$E_{s2} \cdot V_2$ (the 2 ^d gap), kV ² /mm	2040
electrostatic compression	11:1
distance to the beam minimum from the cathode, mm	220

3b. Magnetic system design

Conceptual design of the magnicon magnetic system has been carried out in order to achieve an optimal field profile, to provide maximum tube efficiency. The magnetic system also provides optimal beam matching with the electron gun, and optimal dispersion of the beam in the collector that must handle a peak power up to 200 MW and average power up to 30 kW.

The magnetic system layout integrated with the magnicon RF system and the beam collector is shown in Fig. 6. The magnetic field profile shown in Fig. 6 is tailored to achieve optimal tube performance. The magnetic field up-tapering at the front end of the magnetic system provides both matching of the beam with the magnetic field and adiabatic magnetic compression of the beam down to the desired diameter, quite close to Brillouin limit of 13 mm. The beam trajectories at the beginning of the magnicon magnetic system is shown in Fig. 7. One can see a special trimming coil that allows compensation of stray magnetic fields on the cathode.

The final beam design parameters are presented in Table IV.

Fig. 6. Required axial magnetic field profile (top), and coils, iron yoke and collector layout (bottom). Cavity chain (1-6) is also shown.

Fig. 7. The beam matching with the magnicon magnetic system. Input part of the magnetic system contains pole-piece and iron yoke, first coil of the solenoid and trimming coil for compensating stray magnetic field on the cathode. Sample computed beam trajectories and axial magnetic field profile are also shown.

Table IV. Final beam parameters (550 kV, 363 A).

peak magnetic field in defelection system, Gs	800
beam diameter in the deflection system, mm	13
Magnetic compression	~5:1
total beam area compression	~60:1

3c. Magnicon RF cavity designs

The RF system of the 120 MW magnicon consists of six cavities (one drive cavity, four gain cavities including the penultimate cavity, plus the output cavity). The beam-loaded Q of the deflection cavities is around 220 and the external Q of the output cavity is about 35. Lower beam-loaded Q in the deflection cavities is obtained by increasing the cavity lengths and lowering the guiding magnetic field, so that the beam-wave interaction becomes stronger.

Drive and gain cavities.

All magnicon cavities operate in the TM_{110} mode. The cavity layout with the RF field map and longitudinal distribution of transverse (deflecting) RF magnetic field is shown in Fig. 8. Design parameters of the cavity are listed in Table V.

Two main unwanted dangerous oscillations have been identified; suppression of each is clearly necessary. The first is monotron self-excitation. During the course of 7 GHz magnicon

investigation [20] it was found that the mode TM_{030} was responsible for this effect. This instability was analyzed for the present case, and a cavity length of 167 mm was chosen in order to avoid it. The second potentially dangerous oscillation issue is harmonic generation (amplification). It was found that the frequency of the TM_{431} mode is quite close to the 4th harmonic of the drive frequency for a typical deflection cavity. This may lead to harmonic amplification and breakdown [21]. To combat this possibility, the proper shape of the cavity must be chosen in order to shift the TM_{431} mode frequency with respect to the operating frequency harmonic.

Table V. Parameters of the TM_{110} drive and the first two regular gain cavities.

resonance frequency, MHz	804.3
diameter, mm	456
length, mm	167
aperture, mm	50
quality factor	40,000

Fig. 8. (a) The TM_{110} drive and regular gain cavity layout, and (b) the transverse magnetic field distribution along the cavity axis. All dimensions are in mm.

The third gain cavity has a larger output aperture for the deflected beam, as compared with the first two gain cavities. Parameters of the fourth gain cavity are shown in Table VI. The cavity layout and axial field distribution of RF magnetic field are shown in Fig. 8.

Table VI. Parameters of the third gain cavity.

resonance frequency, MHz	804.3
diameter, mm	456
length, mm	167
input aperture, mm	50
output aperture, mm	65
quality factor	40,000

Fig.. 9. (a) The third gain cavity layout, and
(b) transverse RF magnetic field distribution along the cavity axis. All dimensions are in mm.

Penultimate cavity.

The penultimate cavity has a larger aperture than regular gain cavity to insure the absence of current interception in the RF system in all possible regimes of tube operation. The cavity layout with RF field maps and longitudinal distributions of transverse (deflecting) RF magnetic field is shown in Fig. 10. Both monotronic self-excitation and 4th-harmonic generation were analyzed, and the proper cavity dimensions were chosen in order to avoid them. Note that the maximum surface RF electric field in the penultimate cavity is about 70 kV/cm, which is well below the breakdown limit. The Ohmic losses in the deflection cavities are negligible, except for

the penultimate cavity, in which they are less than 0.2 % of the output power. Design parameters of the penultimate cavity are listed in Table VII.

Table VII. Parameters of the penultimate cavity.

resonance frequency, MHz	804.3
diameter, mm	451
length, mm	167
input aperture, mm	65
output aperture, mm	120
quality factor	39,000

(a)

(b)

Fig.. 10. (a) The penultimate cavity layout, and (b) transverse magnetic field distribution along the cavity axis. All dimensions are in mm.

Output cavity

The output cavity (shown in Fig. 11a) is designed so that the profiles of the RF electric and magnetic fields along the axis are similar, as shown in Figs. 11b and 11c. In that case, the axial forces from these fields nearly cancel, and the axial velocity remains fairly constant during the interaction process. Such field distributions are achieved by increasing the diameter of the cavity near the beam entrance. The maximum surface electric field in the output cavity is less than 70 kV/cm for an output power of 120 MW. Design parameters of the output cavity are listed in Table VIII.

Table VIII. Parameters of the TM_{110} output cavity.

resonance frequency, MHz	800
diameter, mm	495
length, mm	450
input aperture, mm	120
output aperture, mm	240
quality factor (unloaded)	33,000

Fig. 11. (a) The output cavity layout, (b) transverse magnetic field and (c) longitudinal electric field distribution along the cavity axis at a radius of 20 mm. All dimensions are in mm.

In Fig. 11a one can see that the output cavity contains a special choke in order to prevent RF radiation from passing through the output beam aperture, whose diameter substantially exceeds the cut-off limit. Both RF electric and magnetic fields are very small beyond the choke. One can see RF field patterns, in both output cavity and choke. The choke works well within a frequency band of at least 3 MHz. Because the output cavity loaded Q is to be only 35, four output waveguides may be required. The Ohmic losses in the output cavity are about of 0.1% of the output power. The results of 3D simulations are shown in Fig. 12. One can see RF field patterns, in both output cavity and choke. The case is shown when all four waveguides are used for the RF energy extraction. If two waveguides are used (they should be spaced by 90° in azimuthal direction), compensating protrusions should be placed instead of the other two waveguide openings in order to preserve the RF field symmetry [1]. These protrusions may be used for pumping, diagnostic, etc..

Fig. 12. 3D simulation of the output cavity. The cavity geometry is shown including the choke, and output waveguides. The pattern of electric field modulus is also shown (in red).

3d. Beam dynamics optimization.

Beam dynamics in the 120 MW magnicon has been optimized using realistic DC magnetic and RF electromagnetic fields, and a finite thickness electron beam (the beam diameter used in the simulation is 14 mm). The models and codes used are described in detail in ref. [22]. The optimal magnetic field profile, which is necessary to achieve a tube efficiency of 60%, is shown in Fig. 6. Results of time-dependent simulations of magnicon excitation are shown in Fig. 13. One can see that the transient process is smooth, and that the build-up time for steady oscillations is about 0.8 μsec .

Fig. 13. Transient processes in the magnicon. Shown are the RF amplitudes in the cavities and phase in the output cavity, as functions of time from the start of the RF pulse.

Fig. 14. Results of simulations for 120 MW, 800 MHz magnicon amplifier, including space charge.

Shown is an outline of the RF cavities and magnet system, energy E , and radial coordinates of beam electrons R , all as functions of coordinate z along the axis of the tube.

Space charge influence on the beam dynamics is a serious concern for a first-harmonic magnicon because of the strong reduction in guide field in the region between deflection system and the output cavity (see Fig. 6) that may cause dispersion of the high-perveance beam, and thus significant reduction of the tube efficiency. Detailed simulations were performed in order to understand the influence of space charge on the beam transverse dynamics based on the models described in Ref. 22. An example of the beam dynamics simulation taking into account space charge influence on the transverse beam dynamics is shown in Fig. 14. Simulations show that even for 120 MW, 800 MHz magnicon with high beam perveance of $0.89 \times 10^{-6} \text{ A/V}^{3/2}$ space charge effects do not significantly influence transverse beam dynamics. These effects cause some increase in energy spread of the spent beam, but do not reduce the tube efficiency. One can see that the deceleration is relatively uniform, and that the beam loses a substantial part of its energy (60%). The beam trajectories indicate that there is no current interception in the tube. The drive curve is smooth and monotone, and the tube bandwidth at -3 dB level is equal to 1.3 MHz [17].

3e. Beam collector

The beam collector must sustain the full beam average power of 30 kW in the absence of RF drive. In order to maintain long-life operation of the collector, the heat deposition rates should not exceed 50 W/cm^2 . Pulse heating should not exceed the safe limit of 100 C° . The beam collector schematic with dimensions satisfying these requirements is shown in Fig. 15.

Fig. 15. Beam collector schematic with dimensions in mm.

Computed beam trajectories in the collector in the absence of RF drive are shown in Fig. 16, while the corresponding heat deposition profile at full average beam power of 30 kW is shown in Fig. 17. One can see from these figures that the maximum local heat deposition does not exceed a safe value of 30 W/cm^2 for zero drive signal (full beam power). For normal operating conditions with maximum efficiency, the maximum heat deposition is about 15 W/cm^2 , as can be seen in Figs. 18-19.

Fig. 16. Particle trajectories in the beam collector for condition of zero drive power in the input cavity, including three generations of secondary electrons.

Fig. 17. Heat deposition profile at the surface of the beam collector (from point A to point B), for the trajectories shown in Fig. 15, i.e., the case of zero drive power.

Fig. 18. Computed trajectories in the beam collector, including three generations of secondary electrons, for conditions of full RF power operation.

Fig. 19. Heat deposition profile at the surface of the beam collector(from point A to point B), for the trajectories shown in Fig. 17, with full RF power operation.

3f. Summary of results of Phase I study

Fulfillment of Tasks 3a-3e during Phase I allowed a conceptual design to be completed for a 120 MW, 800 MHz magnicon with parameters as shown in Table VIII, repeated below.

Table VIII. Design parameters of 120 MW, 800 MHz magnicon amplifier.

operating frequency, GHz	800
output power, MW	120
pulse duration, μ sec	10
repetition rate, Hz	15
efficiency, %	60
gain, dB	57
bandwidth at -3 dB level, MHz	1.3
beam voltage, kV	550
beam current, A	363
magnetic field in deflecting system, Gauss	800
magnetic field in the output cavity, Gauss	500

This tube performance is confirmed computationally using the gun design shown in Fig. 1, the magnetic system design shown in Fig. 6, the RF cavity designs shown in Figs. 8-12, and the beam collector design shown in Fig. 15. Predicted RF power output is seen to be about the 120 MW goal, with a gain of 57 dB and an efficiency of 60%. For 57 dB gain, the required 800 MHz drive power is about 250 W.

Material presented in this section strongly confirms the feasibility of realizing a 120 MW, 800 MHz magnicon, and provides a strong basis for the work that was proposed for Phase II. But since Omega-P's Phase II proposal was not approved, no further work on this topic has been carried out by Omega-P.

References

1. O.A. Nezhevenko, "Gyrocons and Magnicons: Microwave Generators with Circular Deflection of the Electron Beam," *IEEE Trans. Plasma Sci.*, vol.22 pp. 765-772, October, 1994.
2. G.I. Budker, M.M. Karliner, I.G. Makarov, S.N. Morosov, O.A. Nezhevenko, G.N. Ostreiko, and I.A. Shekhtman, "The Gyrocon—An Efficient Relativistic High-Power VHF Generator," *Part. Accel.*, vol. 10, pp. 41–59, 1979
3. M.M.Karliner, E.V.Kozyrev, I.G.Makarov, O.A.Nezhevenko, G.N. Ostreiko, B.Z.Persov, and G.V.Serdobintsev, *Nucl. Instrum. Methods Phys. Res. A* **269**, 459-473 (1988).
4. V.E.Akimov *et al.*, "Accelerating system of the racetrack microtron", Preprint INP 89-162, Novosibirsk, 1989 (in Russian). Deposited into NTIS database.
5. O.A. Nezhevenko, *Proceeding of 1991 Particle Accelerator Conference*, San Francisco, 1991, (IEEE, Piscataway, NJ, 1992), p.2933.
6. V.E. Akimov, Yu.V. Baryshev, B.S. Estrin, M.M. Karliner, I.V. Kazarezov, E.V. Kozyrev, G.I. Kuznetsov, I.G. Makarov, O.A. Nezhevenko, G.N. Ostreiko, B.E. Persov, G.V. Serdobintsev, M.A. Tiunov, V.P. Yakovlev, and I.A. Zapryagaev. *Proceedings of 1990 European Particle Accelerator Conference*, Nice, 1990, (World Scientific, Singapore, 1991), p. 1000.
7. E.V. Kozyrev, O.A. Nezhevenko, A.A. Nikiforov, G.N. Ostreiko, G.V. Serdobintsev, S.V. Schelkunoff, V.V. Tarnetsky, V.P. Yakovlev, I.A. Zapryagaev, "Present Status on Budker INP 7 GHz Pulsed Magnicon", RF98 Workshop, Pajaro dunes, October 5-9, 1998, AIP Conference Proc. 474, Woodbury, N.Y., 1999, pp.187-194.
8. E.V. Kozyrev, O.A. Nezhevenko, A.A. Nikiforov, G.N. Ostreiko, B.Z. Persov, G.V. Serdobintsev, S.V. Schelkunoff, V.V. Tarnetsky, V.P. Yakovlev, I.A. Zapryagaev, "New Results of 7 GHz Pulsed Magnicon Amplifier Investigations", EPAC98, Stockholm, June 22-26, 1998, p.1897.
9. O.A. Nezhevenko, V.P. Yakovlev, J.L. Hirshfield, E.V. Kozyrev, S.H. Gold, A.W. Fliflet, and A.K. Kinkad, "Performance Of X-Band Pulsed Magnicon Amplifier," in Proc. 2003 Particle Accelerator Conf., Portland, May 11-16, 2003, pp.1128-1130.
10. O.A. Nezhevenko, M.A. LaPointe, V.P. Yakovlev, J.L. Hirshfield, "Comissioning of the 34 GHZ, 45 MW Pulsed Magnicon," *IEEE Trans. On Plasma Science*, vol. 32, No 3, June 2004, pp. 994 – 1001.
11. D. Sprehn, R.M. Phillips, and G. Caryotakis, "Performance of a 150-MW S-Band Klystrons," SLAC-PUB-6682, September 1994; see also AIP Conference Proc. **337**, Woodbury, N.Y., 1995, pp.43-49.
12. D. Sprehn, G. Caryotakis, E. Jongewaard, R.M. Phillips, and A. Vlieks, "X-Band Klystron Development at the Stanford Linear Accelerator Center," SLAC-PUB-8346, March 2000.
13. A. Buenas, G. Faillon, S. Choroba, A. Gamp, "A High Efficiency Long Pulse Multi Beam Klystron for the TESLA Linear Collider," TESLA Report 2001-01
14. A. Buenas, P. Pearce, "A Klystron-Modulator RF Power System for the CLIC Drive-Beam Accelerator," CLIC Note 435, CERN/PS 2000-014.
15. G.S. Nusinovich, B. Levush, D.K. Abe, "A Review of the Development of Multiple-Beam Klystrons and TWTs," NRL/MR/6840-03-8673.

16. The Program in Muon and Neutrino Physics: Super Beams, Cold Muon Beams, Neutrino Factory and the Muon Collider. Editor: Rajendran Raja. Snowmass 2001 documents, <http://www.cap.bnl.gov/mumu/pubs/snowmass01/overarch.pdf>
17. O.A. Nezhevenko, V.P. Yakovlev, J.L. Hirshfield, "High Power Magnicons at Decimeter Wavelength for Muon and Electron-Positron Colliders," EPAC2004, Lucerne, July 2004, pp. 1099-1101.
18. High Voltage Vacuum Insulation, Edited by R.V. Latham, Acad. Press, N.Y., 1995, pp. 403-429.
19. E. Wright, A. Balkcum, H. Bohlen, *et al.*, "Development of 10-MW, L-Band Multiple-Beam Klystron For TESLA," *Proceeding of 2003 Particle Accelerator Conference*, Portland, May 11-16, 2003, pp.1144-1146.
20. E.V. Kozyrev, I.G. Makarov, O.A. Nezhevenko, B.Z. Persov, G.V. Serdobintsev, S.V. Shchelkunoff, V.V. Tarnetsky, V.P. Yakovlev and I.A. Zapryagaev, "Performance of the High Power 7 GHz Magnicon Amplifier", *Particle accelerators*, v. 52, 1996, pp.55-64.
21. O.Nezhevenko, O. Danilov, I.Kazarezov, E. Kozyrev, G. Kuznetsov, I. Makarov, A. Nikiforov, B. Persov, G. Serdobintsev, V. Yakovlev, I. Zapryagaev, "7 GHz Pulsed Magnicon", Report in International Workshop on Pulsed RF Sources for Linear Collider (RF'94), October 2-7, 1994, Montauk, USA, pp.174-183.
22. V. P. Yakovlev, O.A. Nezhevenko, O.V. Danilov, D.G. Myakishev, and M.A. Tiunov, "State of the Art Simulations of Magnicon," AAC2002 Proceedings, Oxnard, June, 2002, AIP Conference Proc. 647, Woodbury, N.Y., 2002, pp. 421-432.
23. Handbook on Accelerator Physics and Engineering, Edited by A.W Chao and M. Tigner, World Scientific, Singapore, 1998.