20 MW Magnicon for International Linear Collider ILC

Classification (subsystem)

linear accelerator RF system

Personnel and institution requested funding

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PROJECT OVERVIEW

Introduction

The overall goal of the R&D program outlined here is to design, build, and test a magnicon amplifier at 1.3 GHz with a peak power output in the range of 20 MW, for the future International Linear Collider ILC that is based on superconducting RF technology. This overall project is to evolve into a collaboration between the Yale Beam Physics Laboratory (YBPL), Omega-P, Inc., and Budker Institute of Nuclear Physics, Novosibirsk. Three-year funding for YBPL in the present proposal is mostly to provide infrastructure needed to accommodate the magnicon experimental test facility; further funding for YBPL is anticipated from a Phase II DoE STTR grant to Omega-P, to follow a pending Phase I SBIR grant for refinement of the design of the 1.3 GHz, 20 MW magnicon, and/or from other sources.

There is broad agreement in the high energy physics community that a linear e^+-e^- collider with a center-of-mass energy E_{cm} = 500-1000 GeV and a luminosity above 10^{34} cm^{-2}s^{-1} is of fundamental importance for the future development of particle physics; it is in many respects expected to be complementary to the Large Hadron Collider LHC (under construction at CERN), and is anticipated to be built as the next large accelerator facility. In 2004, the International Committee for Future Accelerators (ICFA) formed the International Technology Recommendation Panel (ITRP) to evaluate the two competing technologies and to recommend a single choice on which to base ILC. One approach, developed by the TESLA collaboration [1], accelerates beams in 1.3 GHz (L-band) superconducting cavities. The second approach, a result of joint research by the NLC and GLC collaborations [2], accelerates beams using 11.4 GHz (X-band) room temperature copper structures. ITRP recommended that ILC be based on superconducting L-band RF technology [3].

In TESLA [2], considered to be the basis for ILC, the two main linacs would each be constructed from about 10^4 one-meter long, nine-cell superconducting cavities operating at 1.3 GHz. Groups of twelve such cavities would be installed in a common cryostat. The accelerating gradient would be about 25 MeV/m and the final center-of-mass (c.m.) energy would be 500 GeV. RF-power would be generated by some 600 klystrons, each feeding 36 nine-cell cavities. Required peak power per klystron is 9.5 MW, including a 10% overhead for correcting phase errors during the beam pulse which arise from Lorentz force detuning and microphonics. RF pulse length is 1.37 ms, which includes the beam pulse length of 950 μs, and the cavity fill time of 420 μs. The repetition rate is 5 Hz for the major part of the linac, but the 5-50 GeV section stations will run at 10 Hz to alternate between XFEL and linear collider operation. Three versions of 10 MW multibeam klystrons (MBK) have so far been designed and built as candidate RF source for TESLA. The MBK TH1801 (Thales) [4] having a beam voltage of 117 kV and an efficiency of 65% was tested; three tubes were built and one tube is now in use at the TESLA Test Facility. However, the tube still has a problem caused by arcing in the gun [5] and needs improvements in order to achieve stable operation. Another MBK, VKL-8301 (CPI) [6] that demonstrated efficiency of 60%, but with an achieved pulse width of only 10 μs, is under test at this writing. The third MBK, E3736 (Toshiba) has demonstrated parameters close to full design values, namely a peak power of 10 MW, an efficiency of 65%, and operation with a 1 msec pulse width [7]. The major differences between ILC and TESLA are (*i*) a higher accelerating gradient for ILC of 35 MeV/m, which has already been achieved [8], or possibly a yet higher gradient of about 40 MeV/m [9]; and (*ii*) ILC should be upgradeable to a c.m. energy of 1 TeV.

The requirement for the capability of an upgrade in c.m. energy to 1 TeV represents a serious challenge for the RF system, especially for the high-power RF sources. In the simplest scenario of upgrade, the collider would require about 1200 - 10 MW klystrons. The high cost and complexity of this approach have led to suggestions of other scenarios, some which require development of an RF amplifier with a peak power about 18 MW [10]. However, regardless of the details of a given scenario, the availability of a 20 MW amplifier would allow lowering the number of tubes to 300 in the 0.5 TeV option, and to 600 in the 1 TeV option, representing an important step towards reducing the complexity and cost for ILC. But despite its evident appeal, this option has not been realized because development of a 20 MW, 1.3 GHz, 1.5-2 msec pulse-width tube represents a highly serious technical challenge. Even at the 10 MW power level, the three MBK developers are faced with problems caused mainly by breakdown in the gun, impossibility to achieve the desired beam area compression, and increased level of beam current interception. In principle, a single beam klystron (SBK) could be designed for this parameter range, but it will be impractical due to its enormous length.

The program proposed here has as its ultimate goal the laboratory demonstration a 20-MW, 1.3 GHz magnicon amplifier* that would replace two MBK′s, and thus reduce by a factor-of-two the number of tubes required for ILC. The magnicon is a deflection-modulated RF amplifier, which has already demonstrated in a wide range of frequencies from 915 MHz to 34.3 GHz a capability for producing multi-megawatt peak power, very high efficiency, and high gain [11-15]. 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 20-MW magnicon can be substantially shorter than that of an SBK, and similar in size to the RF system employed in 10 MW MBK′s that are now contemplated for ILC.

In the Yale portion of the program as outlined here, laboratory infrastructure would be established in YBPL to allow installation and operation of the magnicon. This infrastructure includes provision of sufficient mains power and of adequate chilled water flow to dissipate the spent power, re-arrangement of an existing access door to provide necessary x-ray shielding, instrumentation to monitor x-ray dose, and data processing instrumentation for monitoring magnicon performance. Under a pending Phase I DoE SBIR grant that would run through April, 2006, Omega-P will on its own carry out design refinements for the magnicon. It is anticipated that joint support for collaborative R&D would then materialize under a follow-on two-year Phase II DoE STTR grant to Omega-P, with Yale as the participating research institution. Until July 2006, the Yale and Omega-P activities would be closely coordinated, but formally independent of one another. Until establishment of the STTR, no Yale facilities will be used for research tasks originating with Omega-P. In the proposal for the Phase II STTR grant that would run until about June 2008, formal linkage is to be established in the manner that is customary between universities and R&D companies operating under STTR auspices. But, because of the long lead time for realization of the infrastructure installations, and since physical modifications of Yale research space should be undertaken with funds directly administered by Yale, independent support is needed to prepare the facilities in advance of final engineering design, installation, and testing of high-power components of the magnicon setup. The modulator, electron gun and beam collector are the first components that would be so tested.

Technical Approach

Several versions of the magnicon have been built, from the decimeter to the millimeter wavelength domains, operating in the first, second and third harmonic modes. The first magnicon gave a power of 2.6 MW at 915 MHz with a pulse length of 30 μsec and electronic efficiency of 85% [11]. That tube, a first harmonic (fundamental) amplifier, was successfully tested in 1985 not only with absorbing loads, but with also a resonant accelerating structure, without use of a ferrite circulator [17]. This success led to projects for development of magnicons at wavelengths from decimeter to millimeter wavelength ranges. A second magnicon is a frequency doubler (or second harmonic amplifier), operating at a frequency of 7 GHz [18,19]. This tube has demonstrated experimentally an output power of 55 MW, an efficiency of 56%, and a gain of ~70 dB in 1 μsec pulses, in very good agreement with simulation results [13,20]. 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

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*Design simulations for the 20-MW, 1.3 GHz magnicon shown in this proposal were obtained by V. P. Yakovlev and O. A. Nezhevenko, of Omega-P, Inc.

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 μsec pulse widths. The power is limited by oscillations in the beam collector [14]. Construction of a new collector was completed recently, and the collector is scheduled to be installed in January 2005. 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 X-band can take place. A high power third-harmonic magnicon at 34.272 GHz has been designed and built as a microwave source to develop RF technology for a future multi-TeV electron-positron linear collider. After preliminary RF conditioning, this tube produced an output power of 10 MW in 0.25 μs pulses, with a gain of 54 dB [15]. These preliminary results already constitute record values for a millimeter-wave accelerator-class amplifier. While the second and third harmonic magnicon amplifier concepts were introduced in order to achieve high power in the cm- and mm-wave ranges, the first harmonic amplifier has higher efficiency and smaller size than harmonic versions; this can be especially critical at decimeter wave lengths.

Preliminary design parameters of a 20 MW, 1.3 GHz first-harmonic magnicon design for ILC are presented in Table I, and the schematic arrangement is shown in Fig. 1.

The electron gun injects a small diameter pencil beam into a chain of cavities forming the RF system. The deflection system consists of a drive cavity (#1 in Fig. 1) and gain cavities (#2 to #7) to provide the required deflection angle. The external magnetic field provides both beam focusing and coupling between the electrons and the RF fields in the cavities. The scanning beam rotates at the frequency of the drive signal, then enters the output cavity (#8) and emits radiation by interacting with the TM_{110} mode. All cavities of the RF system oscillate in the circularly polarized TM_{110} mode at 1.3 GHz. The proposed magnicon amplifier will operate with a 300 kV, 100 A electron beam to meet the requirements for operation in ILC, namely 20 MW peak output power with a 1.5 ms pulse duration, and a 10 Hz repetition rate. The average power level for this beam is thus 450 kW.

Table I. Preliminary design parameters of 20 MW, 1.3 GHz magnicon amplifier.

operating frequency, MHz	1300
output peak power, MW	~21
average power, kW	300
pulse duration, msec	1.5
repetition rate, Hz	10
efficiency, %	~70
gain, dB	>44
FWHM bandwidth, MHz	~2
beam power, MW	30
beam voltage, kV	300
beam current, A	100
beam perveance, $A/V^{3/2}$	0.61×10^{-6}

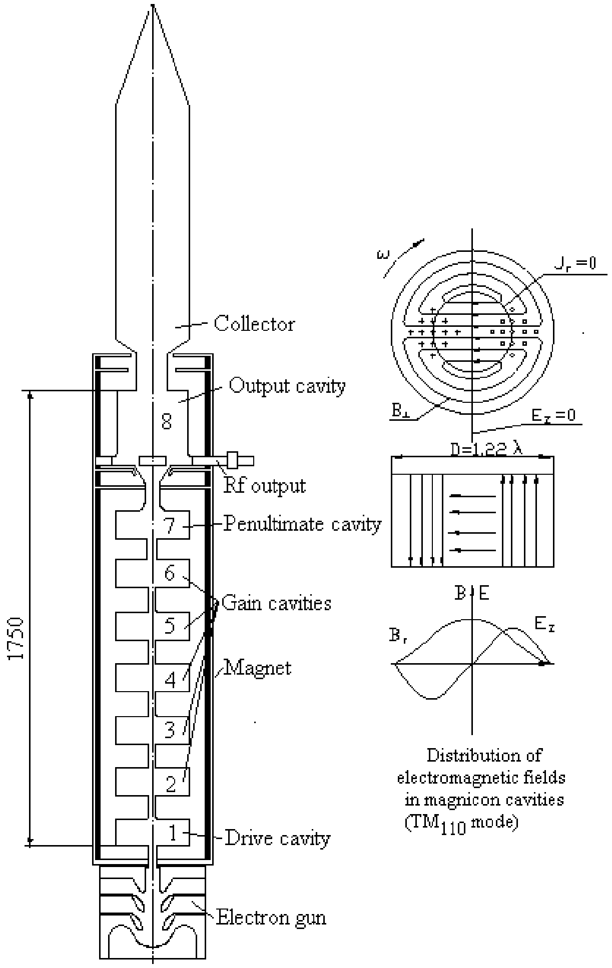

Figure 1. Schematic of 20 MW, 1.3 GHz magnicon amplifier. Note that the 1.75-m length of the RF system is about the same as for the 10 MW Thales MBK TH1801 [4].

The shapes of the cavities are carefully designed to get high efficiency with the smallest possible magnitude of RF fields in the cavities. The maximum surface electric fields in the penultimate and output cavities do not exceed 75 kV/cm. All cavities in the deflection system (#1 to #7 in Fig. 1) are 280 mm in diameter and 100 mm long. For efficient interaction the RF electric and magnetic fields in the output cavity (#8 in Fig. 1) must have nearly similar profiles along the axis, as shown in Fig. 2. Such profiles were obtained by increasing the diameter of the cavity near its entrance [21] as can be seen in Fig. 2. Increase in diameter of the output cavity to 306 mm is also advantageous when using four output waveguides and windows, which may be desirable at the high power level (e.g. as suggested in [10]).

Fig. 3 shows the required magnetic field profile (top) and the coil configuration and iron yoke geometry to achieve this profile (bottom). For effective deflection, the magnetic field in the deflection system should be about 930 Gauss. However, in the output cavity, for efficient extraction of energy, the magnetic field should be about 650 Gauss. One can see that the required levels of magnetic field are quite modest.

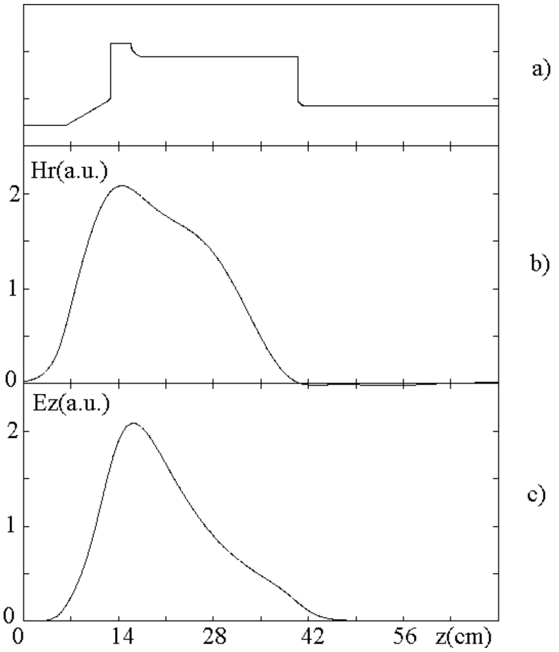

Figure 2. (a) The output cavity layout, (b) transverse magnetic field and (c) longitudinal electric field distribution along the cavity axis at a radius of 20 mm.

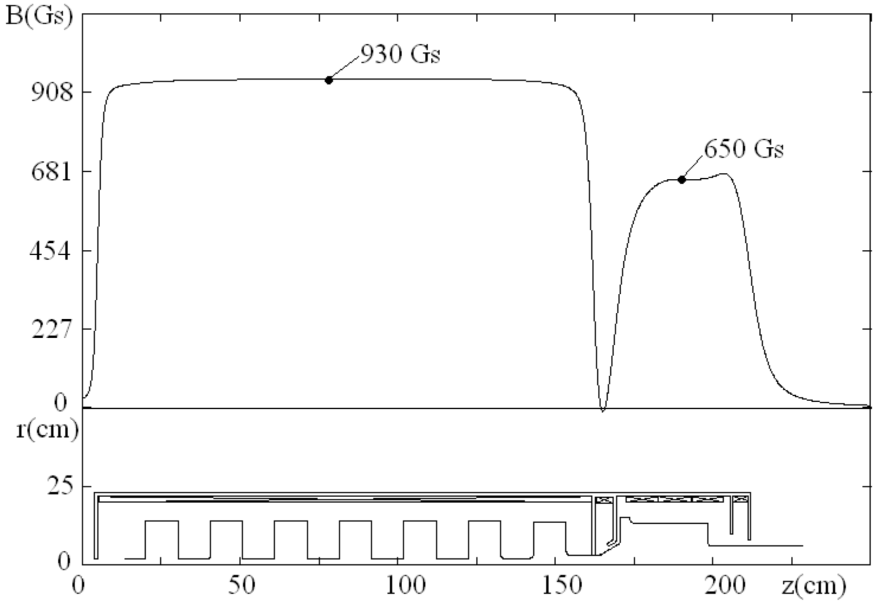

Figure 3. Required axial magnetic field profile (top), coils and iron yoke layout (bottom). Cavity chain is also shown at the bottom.

In Fig. 4 are shown the results of magnicon steady-state simulation. One can see that the deceleration is relatively uniform, and that the beam loses a substantial part of it's energy (>70% on average). The beam trajectories indicate that there is no current interception in the tube. The absence of current interception was proven experimentally in different tested versions of magnicons [11-15].

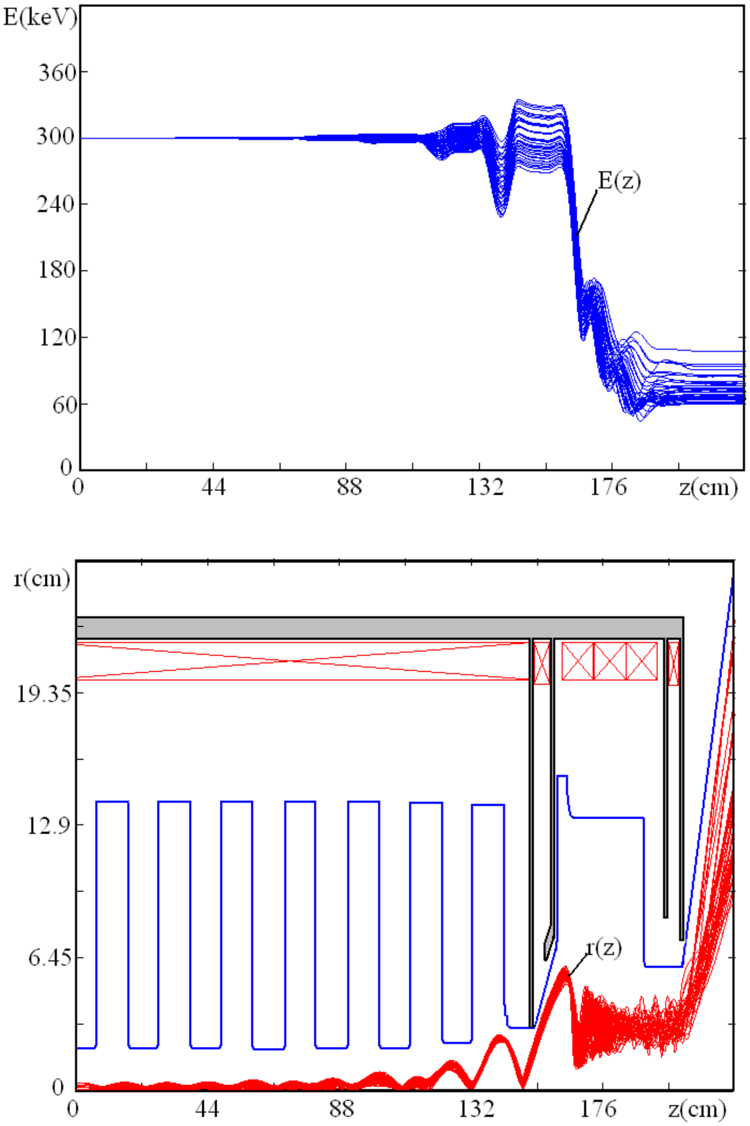

Figure 4. Results of preliminary simulations for a 20 MW, 1300 MHz magnicon. Shown is an outline of the RF cavities, energy *E* and radial coordinates of beam electrons *r*, all as functions of coordinate *z* along the axis of the tube.

Results of time-dependent simulations of transient process in this magnicon amplifier are shown in Figure 5. One can see that the transient process is smooth, and that the build-up time for steady oscillations is about 0.8 μsec. The calculated dependence of the drive curve, i.e. output power *vs.* input power, is shown in Figure 6. The drive curve is monotonic, indicating that the tube operates stably within the full range of output power. Calculated magnicon output power *vs* drive frequency is shown in Figure 7. It indicates that the tube's FWHM bandwidth is about 2 MHz.

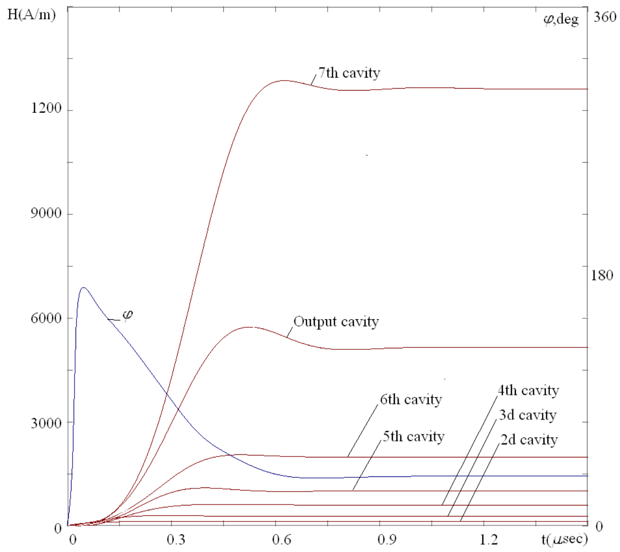

Figure 5. Example of transient processes in the magnicon. Shown are the computed RF amplitudes in the cavities and phase φ in the output cavity, *vs* time from the start of the RF pulse.

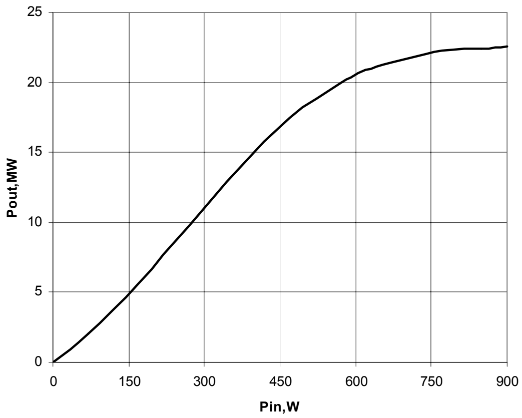

Figure 6. Output power *vs*. input power. Note, in this example, that the output power actually rises to > 22 MW.

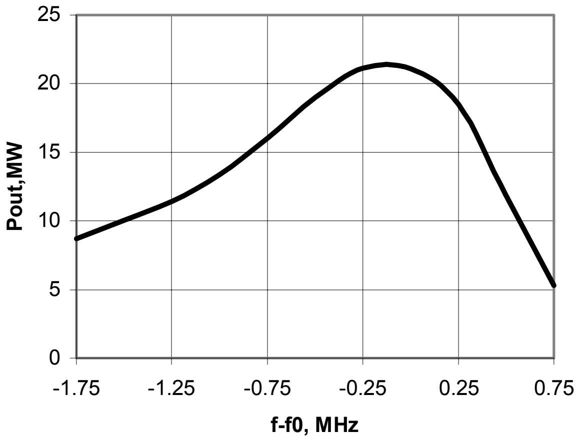

Figure 7. Output power vs. frequency. FWHM bandwidth is about 2 MHz.

Due to the long pulse, the acceptable electric field in the gun must be relatively low. For pulse lengths longer than about 1.0 msec, an empirical relation on the high voltage breakdown condition is given by $E_sV_e < 800$ kV^2/mm, where E_s is surface electric field on the electrode at lower potential and V_e is the voltage between two electrodes [22]. This requirement represents a challenge in the gun design which can be overcome by using a multi-gap (multi-anode) gun concept. In the proposed magnicon, the beam parameters are: beam voltage of 300 kV and beam current of 100 A. To provide these parameters with a pulse-width of about 2 msec, a triple-anode gun with a spherical cathode 8 cm in diameter has been designed, as shown in Fig. 8. The maximum cathode loading doesn't exceed 2.7 A/cm^2, which allows one to expect good cathode longevity of ~100,000 hours according to [23].

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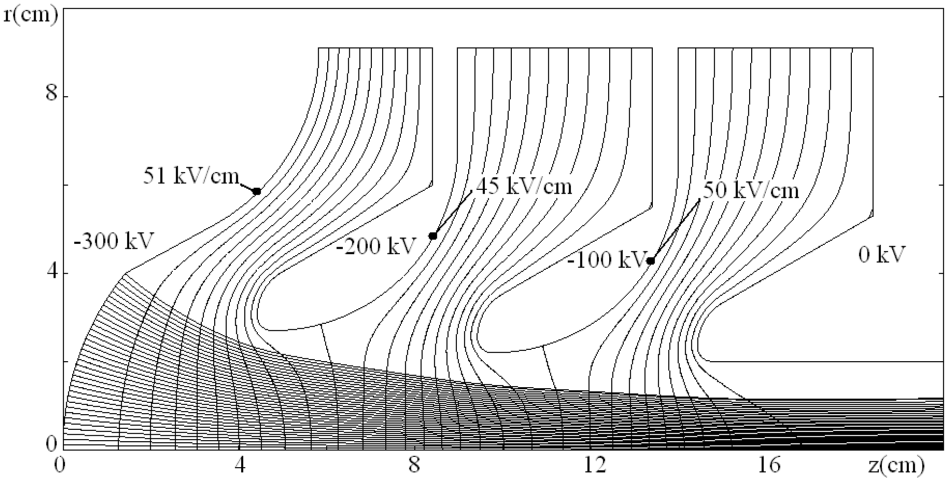

Figure 8. The triple-anode gun layout, trajectories and equipotential lines.

These preliminary design results show that no fundamental impediment exists to realization of a 1.3 GHz magnicon amplifier with a peak power of 20 MW in a pulse-width of 1.5 msec. Logistical issues in the realization of a prototype involve detailed engineering designs and fabrication for the components of the tube, namely the electron gun, RF cavity system, magnetic field, system, and beam collector. A suitable modulator must be obtained, although some compromise in average power (below the 450 kW design beam power) might be required due to ac mains power limitations in YBPL, and to specifications of the modulator that can be acquired within budgetary limitations; however tests at the full pulse width of 1.5 ms are deemed essential for validation of the design. But before engineering designs can be deemed final, space, utility, and radiation shielding parameters must be fixed. Infrastructure needs can be met within an unused 1200 sq. ft. vault in YBPL, a drawing of which is shown in Figure 10. The x-ray shielded control area encloses a 12′×24′×8′ high RF shielded room with two access doors.

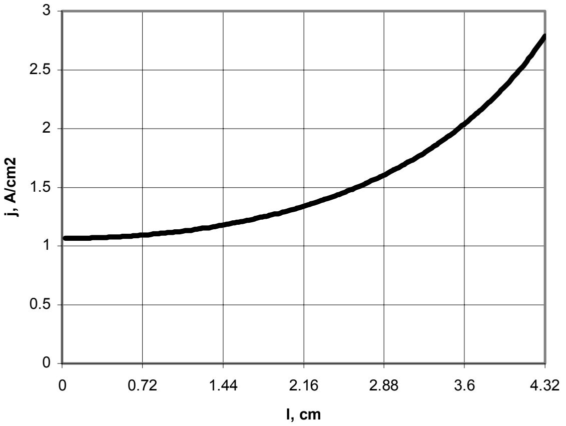

Figure 9. Current density distribution along the cathode surface;
l =0 corresponds to the cathode center.

Table II. Design parameters of the electron gun for a 20 MW, 1.3 GHz magnicon.

beam voltage, kV	300
beam current, A	100
beam power, MW	30
beam perveance, A/V$^{3/2}$	0.61×10^{-6}
pulse duration, msec	1.5
repetition rate, Hz	10
cathode diameter, mm	80
maximum cathode loading, A/cm^2	2.7
number of anodes	3
voltage between the cathode and the 1st anode, kV	100
maximum electric field on the focus electrode (the 1st gap), kV/cm	51
voltage between the 1st anode and 2d anode, kV	100
maximum electric field on the 1st anode (the 2d gap, kV/cm)	45
voltage between the 2d anode and 3d anode, kV	100
maximum electric field on the 2d anode (the 3d gap), kV/cm	50
electrostatic compression	11:1

At present, only 72 kW of 208-V, 3-phase mains power is wired into in the test vault. One goal of the infrastructure up-grade that is proposed is to increase the mains power as much as possible by re-directing power from the 1.5 MW sub-station that powers some of the other areas in YBPL, with the goal of operating the magnicon at a repetition rate of at least 2 Hz. It will also be necessary to install a closed-loop cooling system to dissipate spent power; it is proposed to accomplish this by installing a cooling tower on the laboratory roof (at a position above the 3′ shielding wall) which, together with a pump and heat exchanger, will provide the cooling. An additional modification is needed to allow the large radiation shielding door shown in Fig. 10 to close; it is now blocked by water pipes that were thoughtlessly installed before re-use of the vault was contemplated. These infrastructure changes should be in place before engineering design for the 20-MW, 1.3 GHz magnicon is completed, so that specifications for the mains power needs

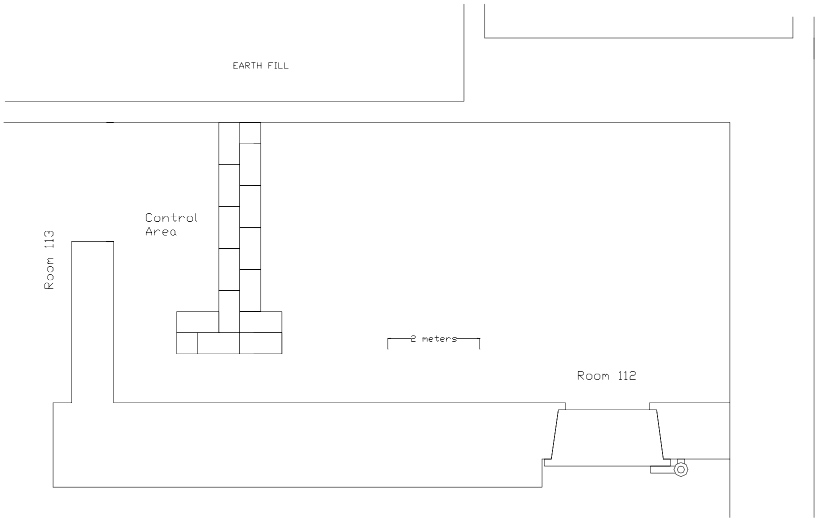

Figure 10. Test vault available within the Yale Beam Physics Laboratory.

will match needs of the available modulator, and so that the physical arrangement in the vault of the (relatively) large experimental magnicon tube and associated components can be optimized. As stated on p. 2 of this document, this would require the infrastructure improvements for the vault to be fully designed, with installations underway by July, 2006, when the formal collaboration sets in between Yale and Omega-P, assuming timely award of a Phase II STTR grant to Omega-P for this project. The third-year portion of the Yale grant requested here is for acquisition, installation, and calibration of instrumentation to monitor x-ray dosage in designated areas of the laboratory, and to diagnostic signals from the magnicon under test. It is appropriate that the costs for these infrastructure installations and instrumentation come from a research award directly to Yale, as they would become integrated as permanent facilities of YBPL.

RESULTS OF PRIOR SUPPORT

There has been no prior support for development of the specific magnicon described in this proposal. However, prior support has been provided by DoE and BINP for a number of versions of the magnicon to be designed and 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 [11]. 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 harmonic (i.e., fundamental) amplifier. The device was successfully tested not only with absorbing loads, but with a resonant accelerating structure as well, without use of a ferrite circulator [17]. This success led to projects for development of magnicons at wavelengths from decimeter to millimeter ranges for different accelerator projects. A second magnicon, also developed in Novosibirsk, is a frequency doubler (or second harmonic amplifier), operating at a frequency of 7 GHz [18,19]. This tube has demonstrated experimentally an output power of 55 MW, an efficiency of 56%, and a gain of ~70 dB in 1 μsec pulses, in very good agreement with simulation results [13,20]. 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.

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FACILITIES, EQUIPMENT, AND OTHER RESOURCES

Since 1992, efforts have been underway in the Physics Department at Yale to establish and equip the Yale Beam Physics Laboratory. Space in the Wright Nuclear Structure Laboratory (WNSL) on the Yale campus vacated by decommissioning of a 50 MeV L-band electron linear accelerator was made available by the Physics Department for beam physics research. However, the Room 112 vault within the Beam Physics Laboratory shown in Fig. 10, used at present for staging and preparation of experiments, requires the refurbishment described above. Utilities include dedicated use of a 2 MW power company substation (1.5 MW at 480 V; and 0.5 MW at 208 V). Approximately 3500 sq. feet of shielded laboratory space has been refurbished so far, including a 10′×10′×100′ buried tunnel, wherein high voltage, high power rf accelerator operations are conducted without danger of human exposure to penetrating radiation. Areas for a control room, experimental staging, cold testing, electronics assembly, and some staff offices are also part of the laboratory. A copious supply of chilled re-circulating deionized water is available for disposal of at least 100 kW of waste heat, with distribution installed along the tunnel from overhead feed and return lines. Experiments that have been carried in this facility include a 10 MW *CARA* (Cyclotron Autoresonance Accelerator), a 4th harmonic 11.424 GHz multi-MW gyroharmonic converter, a 6 MeV rf gun and 17-element beamline, microwave inverse free-electron laser accelerator *(MIFELA)* and microwave inverse Cerenkov accelerator *(MICA).* It is within this laboratory that the 34-GHz magnicon is installed, together with its 100 MW, 1.5 μsec modulator, data analysis, and test equipment. Other installations include a 24 MW XK-5 former SLAC 2.856 GHz klystron, that is powered by a 65 MW modulator providing 3 μsec, 250 kV, 250 A pulses at up to 10 pps. A 3 MW modulator provides 100 kV, 31.4 A pulses synchronized with the klystron pulses to drive the *CARA* injector. Test equipment is available for S-, X-, and Ka-band measurements, including a scalar network analyzer operating up to 40 GHz. The Yale group also carries out experiments on wake field acceleration in dielectric-lined structures and on LACARA at Brookhaven National Laboratory, Accelerator Test Facility in collaboration with Columbia University and Omega-P, Inc. A fully equipped machine shop is located in Yale Gibbs Laboratory, a few steps from WNSL, where a wide range of operations for the fabrication and vacuum brazing of experimental components can be carried out. Other machining, hydrogen brazing, e-beam welding, waveguide fabrication and internal pipe honing necessary for specialized steps in equipment fabrication can be carried out at small shops close to New Haven. Mechanical design can be carried out by mechanical engineers at the Gibbs shop. Electronics design, construction and repair operations are performed by a full-time YBPL technician.

STATEMENT ON BROAD IMPACT

The R&D program proposed here has as its goal the design of the 20 MW, 1.3 GHz magnicon amplifier that would replace two multi-beam klystrons, and thus reduce by a factor-of-two the number of high-power tubes required for ILC. This would allow significant simplification of the RF architecture and reduction in cost of ILC, as well as strengthened participation by US entities in RF source R&D and manufacturing in what is so far fragmented between US, European, and Japanese firms. The technical challenges that will be addressed during the proposed R&D will provide training in high-power vacuum electronics to young researchers and students that is only available at a select few universities, and which is needed to provide know-how and experience required to maintain US capability in this field. Results of the R&D can be applied in the industrialization of the 1.3 GHz, 20 MW magnicon, should it be selected for use in the ILC test accelerator; and in the development of similar magnicons for applications in nuclear physics and high-power microwave systems for defense. Costs to support students are not provided for in the budget presented here. Nevertheless, it is anticipated that opportunities for undergraduate and graduate participation in the program will occur. Such participation could include senior research projects required of all Yale physics majors, and summer employment for graduate students prior to their selection of a Ph.D. thesis topic.

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PROJECT ACTIVITIES AND DELIVERABLES

As stated above, activities to be supported under the grant requested here include infrastructure improvements in the Yale Beam Physics Laboratory YBPL necessary to accommodate an experimental 20 MW, 1.3 GHz, 1.5 ms pulsed magnicon amplifier intended as an RF power source for the superconducting linacs for the future International Linear Collider ILC. Activities would be distributed over the three-year duration of the grant as follows:

FY2005 Project Activities would include redistribution of electrical power that is now available to YBPL from a nearby power vault, so as to provide sufficient power to a modulator to allow generation of an average beam power of at least 90 kW (corresponding to operation at a pulse repetition rate of at least 2 Hz), plus ancillary power needed for the tube's < 1 kG solenoid magnet and other loads. In addition, runs of water piping that now block the x-ray shielding door shown at the bottom right in Fig. 10 would be relocated so as to allow the door to close. **FY2005 Deliverable** would include a written annual report, plus whatever other presentation(s) are requested by the sponsor, or that are appropriate for dissemination at scientific conferences.

FY2006 Project Activities would include installation of a cooling tower on the building roof above the experimental area shown in Figure 10, of a suitable circulating pump, and of a heat exchanger in the experimental area that can be used to dissipate the > 120 kW of heat expected to be generated from operation of the magnicon at a pulse repetition rate of at least 2 Hz. **FY2006**

Deliverable would include a written annual report, plus whatever other presentation(s) are requested by the sponsor, or that are appropriate for dissemination at scientific conferences.

FY2006 Project Activities would include acquisition of instrumentation required to monitor and record x-ray dose levels in areas of the laboratory occupied by radiation-certified personnel during operation of the magnicon, and adjacent areas open to the general public. It is also useful to monitor radiation levels in areas that are never occupied during experimental runs, and to monitor for the presence of any detectable activation. In addition, instrumentation would be acquired for installation in the control area shown in Figure 10 to allow monitoring of diagnostic signals from the operating magnicon. **FY2007 Deliverable** would include a written annual report, plus whatever other presentation(s) are requested by the sponsor, or that are appropriate for dissemination at scientific conferences.

BUDGET JUSTIFICATION

The budget given below includes salary and fringe benefits for one month each per year for Dr. Michael A. LaPointe, Yale Research Scientist; and Mr. Saveliy Finkelshtyen, Yale Research Technician; these are listed together in the category "Other professionals." Levels are based on current Yale salaries, with a 5% increase each year for FY2006 and FY2007. Fringe benefit rate for DoE grants is 42.3% for all three years. No salary request is made for the Principal Investigator, Dr. Jay L. Hirshfield. Equipment acquisitions include $18,000 for a heat exchanger and pump in FY2005; $22,000 for a cooling tower in FY2006; and $25,000 for radiation monitors ($5,000) and signal processing instrumentation ($20,000) in FY2007. These costs are extrapolated from costs in a facilities study carried out for YBPL by Yale Physical Plant Department in 2001. For FY2005, $5,500 is for costs of re-routing plumbing installations, and in FY $6,000 for installation of the chilled-water cooling circuit in FY 2006. Materials and supplies include electrical, electronic, plumbing, and other infrastructure parts and components needed for the installations. Indirect costs are 63.5% of all direct costs, excluding equipment.

Three-Year Budget Request

Item	FY2005	FY2006	FY2007	Total
Other professionals	10,188	10,698	11,233	32,119
Graduate students				
Undergraduate students				
Total salaries and wages	10,188	10,698	11,233	32,119
Fringe benefits	4,310	4,525	4,752	13,587
Total salaries, wages and fringe benefits	14,498	15,223	15,985	45,706
Equipment	18,000	22,000	25,000	65,000
Travel				
Materials and supplies	6,000	5,000	9,000	20,000
Other direct costs	5,500	6,000		11,500
Institution 2 subcontract				
Total direct costs	43,998	48,223	49,985	142,206
Indirect costs	16,509	16,652	15,865	49,026
Total direct and indirect costs	60,507	64,875	65,850	191,232