PROGRESS REPORT

for the period September 1, 2005 – December 31, 2005.

20-MW MAGNICON FOR ILC

DoE award #DE-FG02-05 ER 41394 to Yale University, Sept. 1, 2005 – Aug. 31, 2008

Personnel and Institution requesting funding

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(Collaborating personnel are neither receiving nor seeking funding from this grant.)

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Project Overview

The overall goal of this R&D program is to design, build, and test a magnicon amplifier at 1.3 GHz with a peak power output in the range of 20 MW, as an alternate RF driver for the International Linear Collider ILC. Three-year funding for the Yale Beam Physics Laboratory afforded through this project is mostly to provide infrastructure needed to establish the L-band magnicon laboratory. Further support for this project is to be *via* a sub-grant to Yale within an anticipated Phase II DoE award to Omega-P, Inc. that should follow a present Phase I SBIR grant for refinement of the design of the magnicon, and from other sources. Three industrial firms have already produced 1.3 GHz, 10 MW multi-beam klystrons (MBK's) for near-term application to ILC. Nevertheless, valid arguments that favor use of a 20-MW magnicon in place of two 10-MW MBK's in ILC provide justification to sustain this project, as detailed in part below. In addition, other applications can exist for a 20-MW, 1.3 GHz amplifier, including in the positron source for ILC and in the FNAL proton driver.

Progress Report

In the four months since this project became active at Yale, good progress in making infrastructure laboratory improvements has occurred, and promising advances have been made in analysis of an alternative version of the 1.3-GHz, 20-MW magnicon.

Infrastructure Improvements

In the Project Activities and Deliverables section of the proposal for the first year of this project, two necessary infrastructure improvements were described that included redistribution of electrical power from a nearby power vault, and relocation of runs of water piping that blocked a large shielding door. Both of these improvements have been addressed and nearly completed, as described below. For reference, Figure 10 from the proposal is reproduced here as Figure 1, to show the outline of the new L-Band Magnicon Lab (Room 112) and to provide orientation to the reader for explaining the infrastructure improvements.

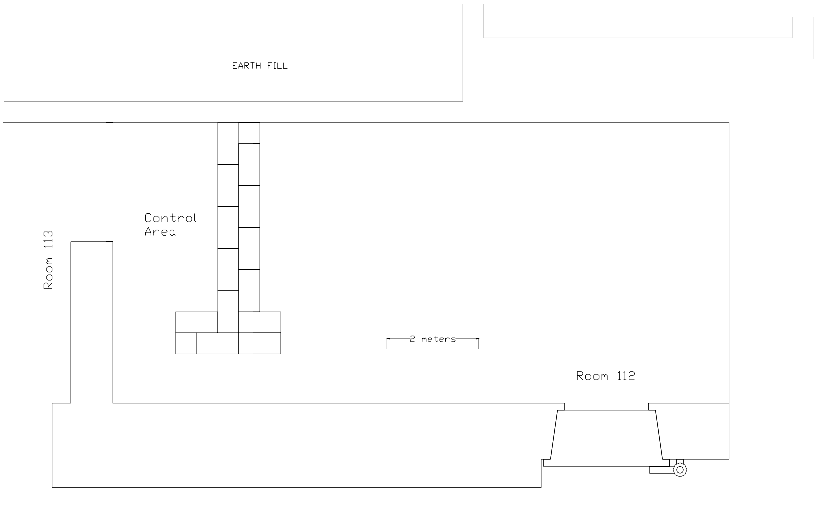


Fig. 1. Drawing of vault dedicated to development of the 20-MW, 1.3-GHz magnicon for ILC.

Within the electrical distribution room (the space whose southern edge is shown at the upper right in Fig. 1), a new disconnect switch and transformer have been installed to supply 208 V, 200 A, 3 phase power (72 kW) for this project. This doubles the available dedicated ac mains power in the L-Band Magnicon Lab to 144 kW, well in excess of the 100 kW that is estimated as necessary to power the magnicon and ancillary equipment. [In this estimate, it is assumed that the magnicon will operate at full pulse width of 1.5 ms, but at a reduced pulse repetition rate not exceeding 2 Hz; this limitation is imposed because of power, cooling, and radiation dose restrictions.] For the time being, further distribution of the new 72 kW service will await a decision on the location of the magnicon modulator. It is preferable for the modulator to be installed in the electrical room, rather than in the L-Band Magnicon Lab itself—but this decision will await detailed information on the design of the modulator. This electrical redistribution and installation task was accomplished by Yale University Physical Plant personnel at a cost of $6,352, a figure that falls within the originally budgeted amount for this purpose.

Relocation has been completed of four water pipes (hot and chilled, supply and return) that prevented closing of the large shielding door shown in the lower right hand corner of Fig. 1. It would have been impossible to conduct planned experiments in Room 112 if this door could not be closed, on account of radiation safety restrictions. Fortunately, two un-used access channels were found in the 6' barites concrete shielding wall through which the relocated pipes could be directed, thus avoiding the costly task of boring new holes in the wall. Still, the quoted cost of $17,500 for this work by an outside contractor selected by the Yale Physical Plant Department exceeded by $11,000 the amount originally budgeted. This $11,000 difference has been made up from the operating budget of the Yale Office of Facilities, and not from the DoE grant. It is significant to report to DoE and the UCLC community this contribution from Yale to the project, representing as it does such a large fraction of the $60,000 grant from DoE for 2005.

For the first time in over 20 years this shielding door has now been closed, as a result of the relocation of the four water pipes. It is remarkable that the 50-year old hinges for this ~20 ton door still function smoothly, allowing a single individual to open and close the door.

Alternate Magnicon Design

A key collaborator in this project, Dr. V. P. Yakovlev of Omega-P, Inc., has carried out simulation studies of an alternative configuration for the 1.3-GHz, 20-MW magnicon that could have important practical implications for use of the tube. The major change in design consists of replacing the TM_{110}-mode output cavity with a TE_{111}-mode cavity. The input and gain cavities remain in the TM_{110}-mode, supporting the classical magnicon deflection gain mechanism. The change allows a reduction of peak surface fields in the output cavity by more than a factor-of-four, provides a smaller degradation in efficiency that can arise from a mistuned magnetic field, while maintaining an electronic efficiency exceeding 75%. The first two attributes imply a much more robust functioning of the tube; while the third impacts the economics of its operation, when compared with 65% efficient MBK's. Here, a summary of these preliminary results is presented.

For the simulation results given here, a 300 kV, 100 A beam is assumed, as produced using a gun similar to that described in the proposal. Figure 2 shows the outline of the TE_{111}-mode output cavity, and the contours of constant rH_ϕ, constituting a so-called field plot. Figure 3 shows the profiles along the cavity axis of transverse electric and magnetic field amplitudes. Figure 4 shows the dc magnetic field profile, the cavity layout, and the magnetic circuit. Figure 5 shows beam trajectories (in red), and beam energies (in blue) along the cavity chain and into the beam collector. Figures 6 and 7 show, for TE_{111}-mode (red) and TM_{110}-mode (blue) output cavities, the frequency response for fixed operating parameters that produce peak output power, and the drive curve at the center of the operating band. It should be stressed that the new results for the TE_{111}-mode output cavity have not been optimized to the same extent as those done earlier for the TM_{110}-mode, and are likely to improve with further work. It should also be stressed that these simulation results do not constitute a tube design, and that many practical issues must be engineered. Notable is the need for a small quality factor $Q = 20$ in the output cavity. This may be achieved by use of four output ports (coaxial or waveguide) instead of two. Of further concern is the relatively close encounter between the beam and the output cavity tunnel edge, with a separation of about 5 mm. Variations in cavity length and taper geometry may serve to increase this separation. Finally, it is clear that design of the beam collector to handle 450 kW of average beam power will not be trivial, although collectors for multi-MW CW gyrotron beams have been successfully built and operated by several laboratories.

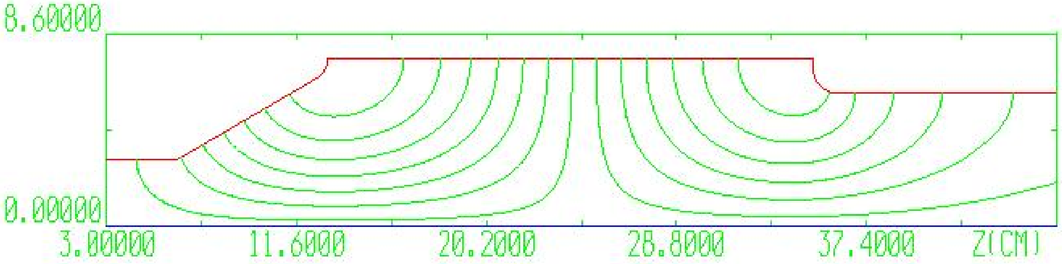
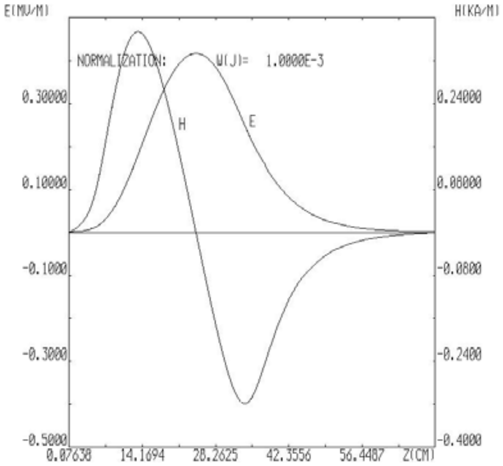


Fig. 2. The TE_{111} cavity layout and field map, i.e. contours of constant rH_ϕ.



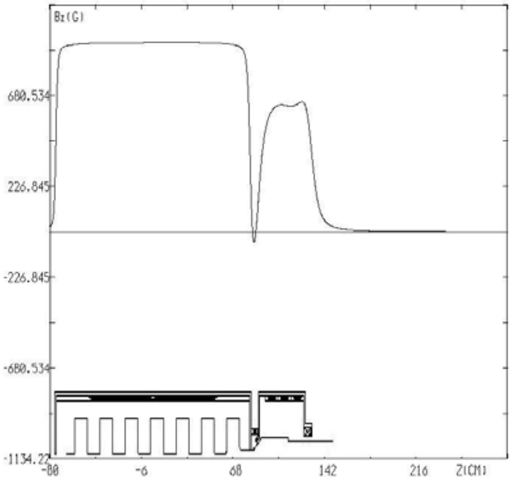


Fig. 3. The transverse electric and magnetic field profiles along the cavity axis.

Fig. 4. DC magnetic field profile, cavity layout, and magnetic circuit.

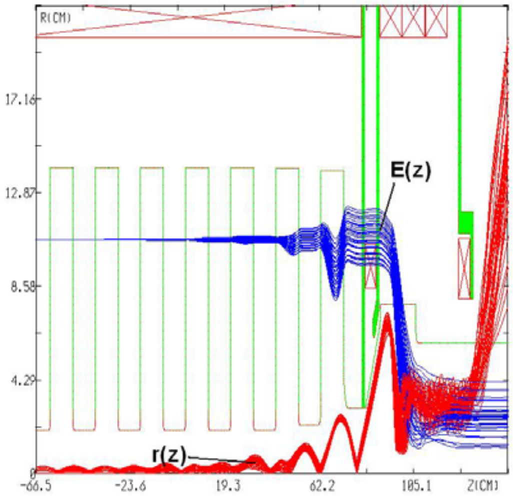
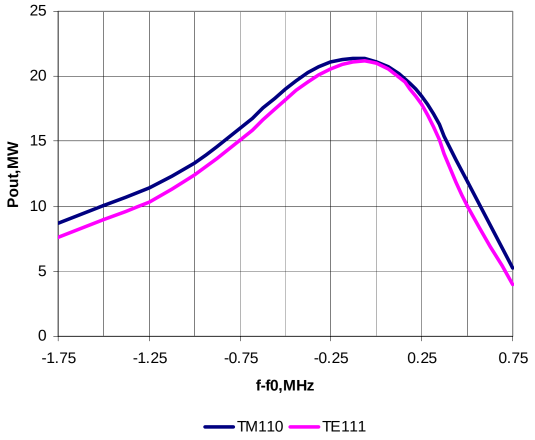


Fig. 5. The beam trajectories $r(z)$ and the beam particle energies $E(z)$.



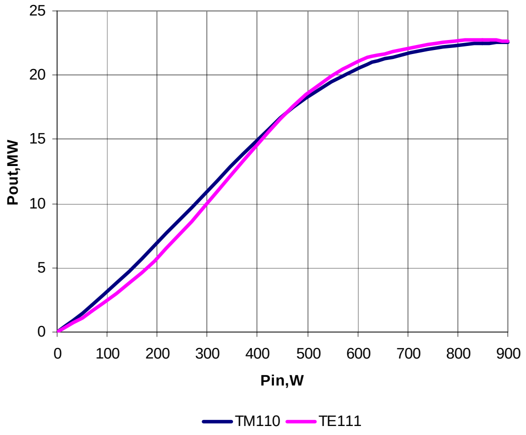


Fig. 6. Tuning curves for TM_{110} and TE_{111} output cavities. BW's are ~2 MHz @-3 dB.

Fig. 7. Drive curves for TM_{110} and TE_{111} output cavities. Peak gain is 44-45 dB.

Table I compares parameters of magnicons with TE_{111}- and TM_{110}-mode output cavities. It is notable that, even without optimization of the design for the former, its performance is virtually identical to that of the traditional TM_{110}-mode version. But the chief virtue of the TE_{111}-mode design is seen in Table II, where the peak electric field in the output cavity is seen to be smaller by more than a factor-of-four than the peak field in the TM_{110}-mode case. This substantial reduction should serve to eliminate the likelihood for breakdown in the output cavity, one of the main limiting factors in achievement of high power in microwave amplifiers.

Table I. Main parameters of magnicons with TE_{111}- and TM_{110}-mode output cavities.

mode for output cavity	input power, W	output power MW	efficiency %	gain dB
TM_{110}	850	22.5	75.0	44
TE_{111}	850	22.7	75.7	45

Table II. Parameters of TE_{111} cavity *vs.* TM_{110} cavity (10 Hz, 1.5 msec, P_{av} = 300 kW)

mode for output cavity	unloaded Q	loaded Q	average power losses in the penultimate cavity, kW	average power losses in the output cavity, kW	$E_{\max}$ in the penultimate cavity kV/cm	$E_{\max}$ in the output cavity kV/cm
TM_{110}	29500	90	2.0	1.0	74	74
TE_{111}	29400	20	2.0	0.3	74*	16

*It is expected, based on designs for other magnicons, that fields in the penultimate cavity can also be reduced significantly by splitting the one penultimate cavity into two that operate in the angle-summing mode. Work to achieve this goal will be undertaken in the coming months.

It is premature to speculate on the initial economic savings from substituting one 20-MW magnicon for two 10-MW MBK's, but not too premature to consider the impressive economic impact of high efficiency. If one compares two RF sources, one with an efficiency of 65% (representative of an MBK), and a second with 75% (as estimated for the magnicon) and further assumes a modulator efficiency of 85%, then for 600 MBK's providing a peak power of 10 MW or 300 magnicons providing a peak power of 20 MW each with 1.5 ms pulse widths and 10 Hz pulse repetition rates, the annual wall-plug power demand at full availability (8760 hours) would be 1.427×10^9 kW-hrs for MBK and 1.237×10^9 kW-hrs for magnicons. The annual demand for ILC using MBK's would exceed that using magnicons by 0.19×10^9 kW-hrs. If electricity cost were to be $0.10 per kW-hr, this amounts to a savings of $19M per year using magnicons in place of MBK's or, at 5% interest, a present value of the savings of about $200M for an assumed 15-year lifetime for the collider.

Future Project Activities and Deliverables. These are copied from the original proposal, since no change in the program is envisioned as yet, after only four months of activity.

> **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.

FY2007 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. This budget, for FY2006 and FY2007, is copied from the original proposal, since no change is envisioned as yet, after only four months of activity.

The budget 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." No salary request is made for the Principal Investigator, Professor Jay L. Hirshfield. Yale fringe benefit rate is 28.3%, and indirect cost rate is 63.5%, excluding equipment. Equipment acquisitions include $22,000 for a cooling tower in FY2006, and $25,000 for radiation monitors ($5,000) and signal processing instrumentation ($20,000) in FY2007. Materials and supplies include electrical, electronic, plumbing, and other infrastructure parts and components needed for the installations.

Item	FY 2006	FY 2007	Totals
Other professionals	10,465	10,988	21,453
Graduate students			
Undergraduate students			
Total salaries and wages	10,465	10,988	21,453
Fringe benefits	2,962	3,110	6,072
Total salaries, wages + fringe benefits	13,427	14,098	27,525
Equipment	22,000	25,000	47,000
Travel			
Materials and supplies	5,873	10,367	16,240
Other direct costs	7,000		7,000
Institution 2 subcontract			
Total direct costs	48,300	49,465	97,765
Indirect costs	16,700	15,535	32,235
Total direct and indirect costs	65,000	65,000	130,000