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280 GHz GYRO-BWO DESIGN STUDY

FINAL REPORT

CONTRACT NO. B048710

JULY 1988

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1.0 INTRODUCTION

This report summarizes the results of a design study of a 280 GHz Gyro-BWO tunable source. The purpose of this study is to identify and propose viable design alternatives for any significant technological risk associated with building an operational BWO system. The BWO system is to meet all of the minimum performance values listed below:

<u>Parameter</u>	<u>Minimum Value</u>	<u>Goal</u>
Peak Output Power	10 kW	>20 kW
Center Frequency	280 GHz	315 GHz
Tunability	+/- 3%	+/- 4%
Slew Rate	6%/10 ms	same
Rep Rate	7 kHz	20 kHz
Pulse Length	0.1-0.5 μ s	< 1 μ s
Duty	1%	5%
Pulse Train Duration	5 sec	cw

The tunable Gyro-BWO system will have three major components: a Gyro-BWO microwave tube, a superconducting magnet, and a power supply/modulator. The design tasks for this study in order of decreasing importance are:

1. Design and specification of the superconducting magnet
2. Preliminary design and layout of a Gyro-BWO microwave tube
3. Specification for the power supply/modulator

2.0 SUPERCONDUCTING MAGNET SYSTEM

Operation of the Gyro-BWO will require approximately 12.9 Tesla at 280 GHz, and approximately 14.5 Tesla at 315 GHz. These high magnetic field amplitudes are only marginally within present superconducting magnet technology. Cost and technological factors provide large incentives for minimizing the high field volume of the superconducting magnet. In particular, the collector design is greatly influenced by the size of the magnet bore chosen.

Several iterations of collector design have indicated that a magnet with a warm bore diameter of 1.75 inches is acceptable. This diameter is set by the required collector ID and the necessary space for cooling paths and structural support. A full specification of the superconducting magnet system is given in Appendix A. Magnets consistent with the listed specifications are available. The price of the specified magnet, capable of producing 12.9 Tesla, is estimated to be \$400K. To add the capability to reach 14.5 Tesla adds significant complications in the design and construction of the magnet system and hence, will increase the price. The price of a 14.5 Tesla magnet consistent with the listed specifications is estimated to be \$500K. These prices include extensive magnet acceptance tests performed by Varian personnel, but do not include installation at Lawrence Livermore National Laboratories (LLNL). It should be noted that these prices are broad numbers based on a one-of-a-kind system.

The magnet specifications given in Appendix A are preliminary and are not the result of a full design of the Gyro-BWO system. The specific magnet design may affect other components of the Gyro-BWO tube. Ideally, the superconducting magnet would be considered part of an overall Gyro-BWO system to be fully designed and delivered as one complete unit. It is important for Varian to be involved in the procurement of the superconducting magnet to properly integrate it into the Gyro-BWO system.

3.0 PRELIMINARY DESIGN AND LAYOUT OF A GYRO-BWO MICROWAVE TUBE

A preliminary engineering sketch of the Gyro-BWO tube is given in Figure 1. The major assemblies for the Gyro-BWO are the electron gun, beam tunnel, interaction circuit, uptaper, collector, and output window. In this study, the collector and output window have been examined in the most detail. A detailed electron gun design was not included as a part of this study. However, the type of gun greatly affects the power supply/modulator design. The technological risks and consequences to the power supply modulator will be discussed for each electron gun configuration.

3.1 ELECTRON GUN AND WIGGLER SYSTEM

The design of the electron gun and wiggler system is very important to condition the electron beam for an effective interaction. Although a detailed electron gun/wiggler system study was not performed, the gun parameters which influence the power supply/modulator were examined. Both a cathode-pulsed gun and a gridded gun were considered. A gridded gun was determined to be the best choice because of power supply considerations. The power supplies considered for the cathode-modulated gun were either unable to meet the specifications or were too expensive when examined in the context of a 7 kHz repetition rate and a 1 μ s rise and fall time. On the other hand, a gridded gun power supply was relatively inexpensive and easy to produce.

A gridded gun is more expensive and yields a poorer quality beam than a cathode modulated gun. Nevertheless, when considering the gun and power supply system as a whole, the gridded gun approach is a lower risk, meets the specifications and has a lower cost. Furthermore, the addition of a third grid corrects the bulk of the electron beam aberrations that are introduced by grids in the gun system. A triple-gridded gun is capable of producing beams essentially equal in quality to those produced by a cathode modulated gun. The remainder of the study will be performed in the context of a triple-gridded gun system.

3.2 WIGGLER/SUPERCONDUCTING FIELD INTERACTION

It is important to appropriately match the magnetic field of the wiggler region into the field of the superconducting magnets to maintain good electron beam quality. The applicable

[illegible]

computer codes have been used to model the coils and magnetic shielding required to correctly match these two fields and to ensure that the magnetic shields are not saturated. Figure 2 shows the field output from the coil/shield geometry. This design fulfills all of the necessary requirements: The magnetic field is flat at 2500 Gauss in the wiggler region; The field has smooth transitions between the superconducting field, the wiggler field, and the 80 Gauss cathode field; and the magnetic shields are not saturated. Furthermore, the system is relatively simple and lightweight.

Increasing the superconducting magnetic field strength to 14.5 Tesla is not expected to substantially influence the design of the field matching system. Although some redesign of the wiggler system may be required to correctly match the two magnetic field regimes, saturation of the magnetic shields is not expected to be a problem at the higher field. Therefore, any wiggler design changes to meet the 14.5 Tesla goal are expected to be minor.

3.3 BEAM TUNNEL

The beam tunnel brings the electron beam from the low magnetic field gun region into the high magnetic field interaction region. The design of the beam tunnel is important to

- allow electron transport through the tube without significant interception on the tube walls
- prevent rf from leaking back towards the gun
- prevent mode conversion of the $TE_{1,2}$ operating mode into a $TE_{1,1}$ mode upon reflection from the upstream edge of the interaction region
- prevent parasitic oscillations from starting in this region
- allow reliable and relatively inexpensive manufacturing of the necessary components

It was initially expected that a beam tunnel with a very small bore adjacent to the interaction region (approximately 500 microns diameter) would be necessary to prevent conversion from the $TE_{1,2}$ mode to the $TE_{1,1}$ mode and to prevent significant amounts of rf

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FIGURE 2. MAGNETIC MATCH TO WIGGLER REGION

power from traveling back towards the gun. This small bore implied a very small clearance between the electron beam and the wall which caused concern over potential beam interception. Subsequent computer calculations have indicated that a much larger bore diameter of approximately 1.7 mm diameter optimizes the beam tunnel with less than 3% conversion of the $TE_{1,2}$ mode. This design also implies that less than 3% of the rf power travels back into the gun region. Considering the difficulty of manufacturing and operating a tube with a 500 micron beam tunnel diameter, the prospects of this larger bore design are very encouraging.

A final concern is the possible oscillation of parasitic modes in the beam tunnel region. While the small bore design could prevent spurious oscillations by making all modes cut-off at the cyclotron frequency, the $TE_{1,1}$ mode may exist at the cyclotron frequency under the large bore design. To prevent this mode from oscillating, the beam tunnel will be smoothly tapered so there are no regions that store energy. An rf loss material will also coat the walls in the beam tunnel, both to discourage spurious oscillations, and to absorb any rf traveling from the interaction region towards the gun.

Meeting the goal parameters would require a slight beam tunnel redesign and geometry modification, but would not pose any significant difficulties.

3.4 INTERACTION CAVITY

The interaction cavity included here is the result of input from LLNL. This geometry should be assumed to be approximate unless confirmed to be otherwise.

3.5 UPTAPER

The uptaper geometry is responsible for

- terminating the Gyro-BWO interaction
- preventing mode conversion as the wall diameter expands into the collector region
- ensuring there are no reflections at the end of the interaction region that would initiate a cavity type oscillation

Each of these parameters were considered in the uptaper design.

The BWO interaction is terminated by dephasing the electron bunches and the rf field. This dephasing may be affected either by tapering the magnetic field and thus the electron cyclotron frequency, or by tapering the wall of the waveguide to change the phase velocity of the rf wave. The superconducting magnet is unable to produce a magnetic field taper of over 0.5% in the interaction region. Thus, the wall taper must be responsible for the interaction termination. Calculations performed at LLNL indicate that an uptaper angle of 2 degrees adjacent to the interaction region is appropriate for terminating the BWO interaction. This information is used in the uptaper design.

Computer codes available at Varian have been used to examine the reflection and conversion of the $TE_{1,2}$ mode as it propagates along the uptaper. The mode conversion is calculated to be less than 1% with the given design. In addition, the reflection at the downstream border of the interaction region has been calculated to be less than 1%. These values are well within acceptable limits for the Gyro-BWO tube.

A slight redesign and geometry modification of the uptaper would be required to meet the goal parameter values, but this would not pose any significant difficulties.

3.6 COLLECTOR

Numerical simulations have been carried out to track the electron trajectories from the interaction region into the collector. These calculations determine the collector magnetic field profile required to spread the electron beam appropriately along the collector.

A single "bucking", or field reducing, collector coil centered about 34 inches downstream from the interaction region is required to reduce the magnetic field in the collector region. This will allow the electron beam to expand to the collector inner diameter within a reasonable distance. The present collector geometry is 0.4 inches in diameter with a distance of 47 inches between the interaction region and the output window. The electrons begin to strike the collector surface about 28 inches from the interaction region.

The collector diameter is smaller than originally envisioned, yet this has not had an adverse effect on the required cooling. In the expected mode of operation the maximum time-

averaged power density on the collector surface is approximately 160 W/cm^2 . This modest power density may be easily dissipated with a relatively simple cooling design. If the duty factor is increased to 5% (while maintaining 10 kW peak output power) the collector power density increases to 800 W/cm^2 . The maximum power density for this case is moderate but still rather easily cooled. In the highest power regime (5% duty, 20 kW peak output power) the collector power density increases to 1.6 kW/cm^2 which is at the upper limits of standard cooling technology. To include a reasonable safety margin in the cooling design, an increasingly expensive and complex cooling technology would have to be employed.

One collector coil setting must be able to adequately spread the electron beam over the collector surface for the entire range of tube operating parameters. Figure 3 presents the results of electron trajectory calculations performed for two different electron beams with one set of collector magnet settings. This calculation assumed the tube was operating at 5% duty factor with a 10 kW rf pulse. The two electron beams that were used spanned the range of parameter space for the tube. The first beam had a beam voltage of 70 kV and a transverse to longitudinal electron velocity ratio, or α of 1; the second beam had a voltage of 60 kV with $\alpha = 2$. Although the power density distributions on the collector surface are somewhat different, the peak power density for the two cases does not exceed 800 W/cm^2 .

The beam from the Pierce gun has a natural tendency to spread out longitudinally on the collector wall because the electron trajectories close to the axis do not expand to the same extent as those farther off axis. The potential problem is that the "on axis" electrons would travel an excessive distance before hitting the collector wall. A scrambler magnet (which is very similar to a wiggler magnet) has been added to the design to aid in collecting these electrons. A transverse field magnet has also been added at the end of the collector to ensure that no electrons are allowed to reach the output window.

A "no profile" water connection fitting is proposed for the collector cooling water supply. This fitting does not add to the diameter of the collector so that the smallest bore superconducting magnet may be used while still allowing the collector to slide through the magnet bore during assembly. The details of water connections may be adjusted for the convenience of the customer.

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FIGURE 3. COLLECTOR POWER DISTRIBUTION

3.7 OUTPUT WINDOW

The output window for the Gyro-BWO must have a low voltage standing wave ratio (VSWR) across a relatively broad band to allow the rf power to leave the interaction region and to prevent the onset of cavity-type oscillations. Of course, the window must also be strong enough to withstand the appropriate thermal and mechanical stresses. Unfortunately, these requirements may be contradictory in some cases. Three window options have been examined:

1. A moth eye window
2. A half-wavelength thick window made of cubic Boron Nitride
3. A window that is a small fraction of a wavelength thick made from diamond or amorphous hydrogenated Boron Nitride

Figure 4 compares the reflectance characteristics of these three windows.

3.7.1 Moth Eye Window

The moth eye window will be used as the benchmark for our analysis of window options. The results available from a moth eye window have been declared acceptable by LLNL, and thus, the moth eye window will, at least, be a backup option if not the accepted solution.

The classical moth eye window consists of a transparent slab of material which has pyramidal structures machined into both faces. The frequency bandwidth of these windows is a function of the base and the height of the pyramids¹. Experimentally, the power reflectance of these windows in the frequency range of interest is 5-10% which corresponds to a VSWR between 1.6 and 2.0. One of the reasons for these relatively high reflectance values is the difficulty in producing the appropriate structure on the window faces. The company that produced MIT's moth eye windows, Fischer Tool, has indicated that achieving the desired height of the pyramidal structures is particularly difficult. Also, the interface between two adjacent pyramids has a significant radius of curvature instead of the relatively sharp intersection that is desired. Ma and Robinson have discovered that inverse pyramids on the

FIGURE 4. WINDOW REFLECTION CHARACTERISTICS

window surface are easier to fabricate and appear to lower the VSWR to slightly over 1.3 in the range of interest ². This form of moth eye shows promise but requires further study.

The moth eye window may be fabricated from essentially any window material, although fused silica or sapphire are the most likely candidates. It may also be made from any reasonably thick (at least 1 mm solid space) slab of material with the appropriate diameter. The thickness of this window implies that there will be no difficulty for the window of interest to withstand atmospheric pressure. Also, since this is a low power application, there will be no significant thermal stresses as long as a window material with a reasonable thermal conductivity (such as sapphire) is used.

3.7.2 Half-Wavelength Cubic Boron Nitride Window

A second option for the broadband window is a thin slab of cubic Boron Nitride whose "optical" thickness is a half-wavelength at 300 GHz. This window would have a VSWR below 1.6 between 280 GHz and 320 GHz, which is superior to the electrical characteristics of the classical moth eye window. Also the thickness of approximately 200 microns for this window is quite sufficient to withstand atmospheric pressure.

Upon further examination, this option was rejected. The window material significantly degrades if it is brought above 700 degrees Celsius. This is disadvantageous in construction and processing of the tube. However, the most significant problem is related to the production of this material. To be able to appropriately place the center of the passband of this window the material thickness would have to be specified to within ± 2 microns. Sumitomo, which would be the supplier of this material, was unwilling to specify a tolerance finer than ± 15 microns. This tolerance range would allow the center of the passband to vary by ± 20 GHz which would allow unacceptably large VSWR values to reside in the frequency band of interest.

3.7.3 Thin Diamond Window

A diamond window that is only a small fraction of a wavelength thick is potentially the most attractive solution. The windows are very broad band and can have VSWR values as low as desired depending on the ability of the window to hold off vacuum. This is very attractive in terms of preventing cavity-like oscillations in the BWO.

The greatest concern for thin diamond windows is the ability to withstand atmospheric pressure. Diamond is an exceptionally strong material with an extremely good thermal conductivity, but very thin diamond films are being considered for windows. Finite element calculations using diamond strength numbers from a potential diamond supplier, Crystallume, indicated that a 2 micron thick, 1 cm diameter window would hold off atmospheric pressure with almost a ten fold safety margin. However, no windows of the desired geometry have been experimentally tested to withstand atmospheric pressure and it is unclear whether the Crystallume diamond strength values may be consistently realized in bulk windows. Linearly scaling data on very small (250 micron diameter), very thin (0.45 micron) windows from Crystallume implies that a window 2.5 mm in diameter and 5 microns thick would be adequately strong. This may be a solution, although the validity of this scaling is in doubt. Crystallume is beginning a program of testing thicker, larger diameter, freestanding diamond windows which will provide some relevant results in early 1989. Varian will keep up to date on these developments.

3.7.4 Thin Amorphous Boron Nitride Window

An alternative to a thin diamond window is a thin amorphous Boron Nitride window. This window has rf characteristics that are virtually identical to those of the thin diamond window. The advantage of amorphous Boron Nitride is that a few micron thick film of this material can be produced presently at the full collector diameter with sufficient strength to withstand atmospheric pressure. Nevertheless, there are still concerns about the ability of this material to tolerate heating for a braze cycle or bakeout. Varian has obtained several samples of this material and will be performing a number of tests to determine its suitability for window applications. It should be noted that there are presently no commercial suppliers of this material although the production technology is fairly well developed.

3.7.5 Conclusion

Currently, the only developed window technology for the 280 GHz gyro BWO is the moth eye window technology. There are several window options which have potential to improve the moth eye window both in terms of simplicity and performance, although these windows are unproven. Hopefully, progress will be made in these alternate window technologies which will allow their use in an operational tube.

Operation at the full goal parameter values implies a ten fold increase in the average rf power delivered through the output window. Nevertheless, this does not present any significant difficulties unless the window thermal conductivity is particularly poor. The amorphous Boron Nitride has a very poor thermal conductivity and may not be applicable at these powers. At present, there is insufficient material information to fully analyze the applicability of this window material.

The output rf flange is approximately sized in Figure 1. Details of this flange design will be determined later for best flexibility.

3.8 VACUUM CONSIDERATIONS

The issue of vacuum pumping the collector region has been examined for the tube. One of the most important considerations in pumping this region is maintaining the minimum collector OD to allow the tube to be slipped through the small bore superconducting magnet. To achieve this, the collector region will be pumped through a coaxial manifold leading into the gun region, which will be designed to have adequate pumping for the entire tube. The collector region vacuum port will be placed approximately 12 inches downstream of the interaction region so the vacuum manifold and the collector cooling manifold will be completely separate.

4.0 POWER SUPPLY / MODULATOR SPECIFICATION AND COSTING

The power supply/modulator for the triple-gridded gun is specified in Appendix B. It should be emphasized that the power supply is an integral part of the tube and thus, will interact with the final detailed design of the Gyro-BWO. It is very important that the power supply design remain up to date with the tube design and thus, that Varian be involved in the procurement of the power supply. Ideally, the Gyro-BWO tube/power supply system would be integrated into a consistent unit to ensure that all of the components interact in the optimum manner.

The price of the power supply/modulator specified in Appendix B is estimated to be \$475K. This price includes construction of the power supply/modulator plus installation and testing of the supply at LLNL.

This power supply is designed for the minimum performance parameters. Some redesign would be required to scale the power supply to higher average power goal level of operation. This does not greatly add to the power supply cost unless the series tube must be replaced. This series tube would probably have to be replaced if operation at the full goal parameter values was desired.

5.0 SUMMARY

There are no significant barriers to the design and construction of a full 280 GHz Gyro-BWO with the listed specifications:

- an appropriate superconducting magnet has been specified, and is commercially available
- a beam tunnel has been designed with the appropriate rf properties, while still allowing transport of the electron beam without significant risk of beam interception
- a collector has been designed with rather modest cooling requirements
- the broadband window requirement is met by the moth eye window

Of all of the subsystems of the tube, the status of the moth eye window is the most doubtful. There are clearly superior alternatives to the moth eye window which will probably be developed within the next year or two. Nevertheless, these alternatives are not currently available and their future development is not ensured.

6.0 REFERENCES

1. Ma, J.Y.L., M.M. Blanco and L.C. Robinson. "Night Moth Eye Broadband Waveguide Window." Proceedings of the Seventh International Conference on Infrared and Millimeter Waves, Marseille, France (Feb. 1983) p. 247.
2. Ma, J.Y.L. and L.C. Robinson. "Night Moth Eye Window for the Millimetre and Sub-millimetre Wave Region." Optica Acta, Vol. 30, No.12, 1983, pp. 1685-1695.

APPENDIX A
SUPERCONDUCTING MAGNET SPECIFICATION.

1.0 INTRODUCTION

Varian is currently developing a Gyro-BWO microwave tube to generate electromagnetic radiation at 280 GHz. This Gyro-BWO will consist of three distinct elements

1. An electron gun to generate the electron beam
2. An rf interaction region to convert electron kinetic energy to electromagnetic energy
3. An electron collector to gather the spent electron beam

Each of these three elements requires the appropriate magnetic field to operate properly. In particular, the magnitude, uniformity and alignment of the magnet field are crucial parameters. Of course, reliability and ease of use are also primary considerations in the design of this magnet.

2.0 SPECIFICATION

The superconducting magnet system for the 280 GHz Gyro-BWO should be a turnkey system including all of the necessary peripheral equipment and power supplies to make a stand alone system. The magnet is subject to the requirements detailed below.

The magnet will consist of a solenoidal coil and a pair of transverse trim steering coils. The superconducting magnets will be enclosed in a vacuum dewar to maintain a liquid helium environment for the coils. The system will include power supplies, a magnet controller and cryogen transfer equipment. The remaining specification will be divided into the following sections:

1. Coils and Dewar
 - A. Superconducting Coils
 - B. Vacuum Dewar
2. Electronics Rack
 - A. Power Supplies
 - B. Magnet Controller
 - C. Cryogen Level Indicators
3. Additional Items
 - A. Cryogen Transfer Equipment
 - B. Acceptance Test Procedure
 - C. Drawings and Operating Instructions
 - D. Warranty

2.1 COILS AND DEWAR

The coils and dewar form an integral assembly and should be received in an assembled condition. Furthermore, the assembly should be able to withstand the presence of a 1 inch thick, 12 inch diameter, steel or iron plate oriented perpendicular to the magnet axis at a distance of 19 inches along the axis from the central field region.

2.1.1 Superconducting Coils

The system will consist of two distinct sets of coils: the main interaction region coils and the transverse trim steering coils. Each set of coils may consist of many separate coils. No persistence switches will be included in the system. Each coil in the system will be separately energized.

2.1.1.1 Main Interaction region coils

The main interaction region coils will be solenoidal. The inner diameter of the coils will be consistent with a 1.75 inch diameter room temperature bore for the dewar. The outer diameter of the coils may be varied as required to obtain the desired field profiles. The maximum length of the coils will be consistent with a dewar bore length of under 34 inches.

The main interaction coils should be able to produce 12.9 Tesla on axis that is flat to within $\pm 0.25\%$ over the central ± 0.3 inches. Also, the axial field should smoothly drop to 1900 Gauss ± 500 Gauss on either side of the magnet at a distance of 20 inches from the interaction region.

If specified in the purchase order, the coil and dewar design should be made compatible with operation of the coils at 14.5 Tesla. This may be accomplished through a reduction in the helium bath temperature if necessary.

2.1.1.2 Transverse Trim Steering Coils

The transverse trim steering coils will produce dipole fields perpendicular to the axis of the bore in the x and y directions. The coils will be wound around the outside of the main cavity coils, so their size will be determined by the outside diameter of the main cavity coils. The pair of coils will be capable of producing a transverse field of at least 250 Gauss on the axis of the bore in the center of the main solenoidal coils. The goal for the transverse field strength from these coils is 500 Gauss.

2.1.1.3 Transverse Field Specification

To provide for proper transmission of the electron beam inside the tube, the superconducting coils must be precisely aligned with the mechanical axis of the bore. The ratio of the transverse field to the axial field (B_t/B_z) must be less than 0.2% for all points lying on the axis within ± 18 inches of the peak field position. The vendor will either make provisions for aligning the magnets with the mechanical axis or for aligning the mechanical axis with magnets. The alignment procedure will be a part of the acceptance test.

2.2 VACUUM DEWAR

The vacuum dewar will maintain a liquid helium environment for the superconducting coils subject to the constraints enumerated below. A liquid nitrogen shield may be used to lower the boiloff rate. The dewar must be constructed of nonmagnetic materials, preferably stainless steel. The dewar will have a cylindrical room temperature bore. Since the inside bore must mate with the Gyro-BWO, the dimensions of the bore must be held to very close tolerances. This diameter is to be 1.75 inches $\pm$ 0.100 - 0.065 inches. The dewar will be operated with the inner bore oriented horizontally. The outside diameter of the dewar may be varied in order to meet other technical requirements such as boiloff rate. However, the minimum outside diameter is preferred and in no cases will it be greater than 34 inches. The center of the main coils should be positioned within ± 0.5 inch of the center of the dewar bore. The length of the dewar bore will be no longer than 34 inches.

The top plate of the dewar must be capable of supporting the weight of the dewar assembly including cryogenics, so that the dewar can be lowered into position using a hoist. Lifting eye fixtures will be provided which can be attached to the top plate of the dewar for this purpose.

All electrical connections and transfer tube connections will be located at the end of a service stack. The height of the service stack above the base of the dewar will not exceed 6 feet. The fill and vent ports for helium and nitrogen will be able to withstand application of a heat gun with no damage.

The vacuum integrity of the dewar will be checked using a helium mass spectrometer with a minimum sensitivity of 4×10^{-8} Atm. cc/sec for helium. To assure the long term vacuum

stability of the dewar, the vacuum seals in the dewar will be either weld joints, metal gasket seals or metal wire seals. Preference will be given to an all-welded dewar construction. Ideally, the vacuum would not require re-pumping before cooldown. The vacuum vessel will be equipped for positive pressure relief. Access to the vacuum vessel will be provided through a port equipped with a vacuum valve, a 2.5 inch diameter ConFlat flange and a cap. The valve will be located either under or next to the diagonal service stack.

The helium boiloff rate of the dewar with the coils fully energized will be less than 1.25 l/hr at 12.9 Tesla. If applicable, this boiloff rate will be less than 1.5 l/hr at 14.5 Tesla. The system will require refilling with liquid helium no more than once every 48 hours when under continuous operation at full field. After a shutdown of 72 hours the temperature of the liquid helium vessel will not exceed 77 K and the vacuum envelope will not require repumping.

A label will be affixed to the outside of the dewar clearly stating the number of turns in each coil, the system model number and the serial number of the system.

3.0 ELECTRONICS RACK

The power supplies, magnet controller and cryogen level indicators will be supplied and mounted in a standard 19 inch rack. Installation at the customer site will involve no wiring of interconnects. A 60 foot cable will be provided to connect the electronics to the magnet unless another length is specified on the purchase order. The cable will provide connection to all coils and the cryogen level indicators by means of a quick disconnect plug(s). The power supply end of the cable will be equipped with spade lug connectors. All electronics will use line voltages of either 110 volts or 208 volts at 60 Hertz unless otherwise specified on the purchase order.

3.1 POWER SUPPLIES

A separate power supply will be provided for each coil in the system. The power supplies will be constant current supplies with an output rating of at least 20% greater than that required to operate the magnet coil at full-rated field. The current will be resettable to within 0.1% of full-rated output. Current regulation will be 0.1% of full-rated output. Current will be indicated by a 4-1/2 digit digital meter with a resolution of at least 0.010 amps. All adjustments and trims on the power supplies will be by means of ten-turn potentiometers or other devices with a resolution of at least 0.1% of full-rated output. Variation of current due to either load effects or source effects will be less than or equal to 0.02% of the current plus 2mA. Charging time of the coil to full-rated field will be less than 30 minutes. The settling time of the power supplies after a 1% change in the current-limiting control will be less than 60 seconds. Charging of the coils will be accomplished either with a single step of voltage or by application of a voltage ramp. The vendor will provide an automatic voltage ramp if necessary. The power supply controls will include current-limiting ten-turn potentiometers for all coils and polarity switches for the transverse trim coils. The polarity switches will be guarded to prevent accidental switching of the polarity while the coil is energized.

3.2 MAGNET CONTROLLER

The magnet controller consists primarily of the high and low current alarms. It may also include the power supply controls, the liquid helium level gauge, the liquid nitrogen level indicator and the digital current meter(s). The alarm system for the magnet controller will consist of undercurrent and overcurrent alarms for each coil as well as a low helium level alarm. The under current and overcurrent alarms will be settable to any current from zero to the maximum operating current by means of ten turn potentiometers. The current alarms will

open a relay when activated. The relays will be connected in series with a pair of connectors provided on the back of the controller for connection to an external interlock chain. The circuit will be closed when the system is normal and open when an alarm condition exists. The circuit will also be open when line power is removed from the magnet controller. Internal to the controller, switches will be provided to bypass any of the alarms. In addition, front panel status lights and reset buttons will be provided for each alarm. In the event that any of the alarms are tripped, the circuit will remain open in the alarm condition and the front panel status light will remain illuminated until the reset button is pushed. The alarm terminals will be clearly labeled on the back of the controller. The low liquid helium level alarm will be provided with its own pair of connectors at the back of the controller. The other requirements for this alarm are identical to the current alarms.

3.3 CRYOGEN LEVEL INDICATORS

3.3.1 Helium Level Indicator

The helium level indicator will indicate the level of liquid helium in the dewar on a scale of 0-100% with an accuracy of 2%. The level will be indicated by a digital meter with a resolution of 1%. The indicator will have full, caution and low level lights with user adjustable threshold levels. The indicator will have two modes of operation. First, it should operate in the continuous mode to indicate liquid helium level on a real-time basis. The second mode of operation will be intermittent operation to minimize heat input to the dewar. The indicator will take readings at a preset interval and display the last reading during the interval. The interval between readings will be adjustable from 5 minutes to 60 minutes. An analog output signal of 0-100 mV must be supplied via a BNC connector on the level indicator. The analog signal will be suitable for driving a strip chart recorder.

3.3.2 Nitrogen Level Indicator

If liquid nitrogen is required, an indicator will be provided to show when the liquid nitrogen needs to be refilled and when the liquid nitrogen chamber is full. This may consist of two lamps that light when the liquid level is too low or when the nitrogen can is full. The indicator should be suitable to drive a solenoid valve in a liquid nitrogen auto-fill system.

4.0 ADDITIONAL ITEMS

4.1 CRYOGEN TRANSFER EQUIPMENT

All necessary cryogen transfer equipment will be included with the system. This will include a liquid helium transfer tube, equipment for pre-cooling the dewar and tubes for transferring liquid nitrogen. The helium transfer line will be a vacuum insulated coaxial structure and will show no condensation or icing on the outside surface when used to transfer liquid helium. The outside diameter of the ends of the line will be 3/8 of an inch. The end that goes in the portable storage dewar will be 56 inches long. The corrugated section between the storage dewar and the magnet will be at least 134 inches long unless otherwise specified on the purchase order. An uninsulated tube will be provided for pre-cooling the helium can with liquid nitrogen. This tube will also be suitable for purging the liquid nitrogen from the helium can. Connections will be provided on the dewar to allow pressurization of the helium can and will also provide a connection that will allow a rough vacuum to be drawn on the helium can after the liquid nitrogen is purged. At least 50 feet of clear tubing will be provided for liquid nitrogen filling operations. The tubing will be suitable to fit over a 3/8 inch pipe or hose barb from the liquid nitrogen source.

4.2 ACCEPTANCE TEST PROCEDURE

The acceptance test procedure is an integral part of the verification of system performance and as such documents compliance with the specification. The test procedure will consist of at least the following tests:

1. Dimensional inspection of the outside of the vacuum dewar
2. Helium leak check of the vacuum dewar
3. Measurement of the vacuum level in the dewar
4. Coil resistances (room temperature and liquid nitrogen temperature)
5. Liquid nitrogen and liquid helium consumption for cool-down and fill

6. Liquid nitrogen and liquid helium level indicator operation
7. Individual coil inductance measurement
8. Individual coil field versus current measurement
9. Axial field profiles
10. Transverse field measurement and alignment of magnetic and mechanical axes
11. Transverse coil field profile
12. Liquid helium boiloff rate measurement
13. 48 hour liquid helium hold time measurement
14. 72 hour coil temperature test
15. Maximum field quench test
16. Power supply output current and stability tests
17. Functional tests of the electronics rack

Note that these tests are the minimum requirement. Additional tests may be necessary.

4.3 DRAWINGS AND OPERATING INSTRUCTIONS

The magnet system will include engineering drawings, two complete sets of operation and maintenance manuals, and all test data from the test procedures. The engineering drawings will include a detailed outline print with all dimensions indicated, a drawing showing the internal structure of the dewar and coils, and a description of any electronics to be

supplied including schematics. The manuals will include at minimum: description of operation, block diagrams, detailed schematics, mechanical layout, parts list, and operation, maintenance, and check-out procedures.

4.4 WARRANTY

The magnet system will be covered by a twelve-month warranty, to start the day the system is accepted at the customer site. The warranty is to be non-prorated. The warranty will protect against defects in workmanship or design that would affect the specification compliance of the system.

APPENDIX B
POWER SUPPLY / MODULATOR SPECIFICATION

STATEMENT OF WORK

This specification covers the requirements for a grid pulse modulated power supply system to operate a 280 GHz Gyro-BWO. The system consists of an ac distribution and primary control system, a beam power supply, a grid pulser (see Figure B-1), a gyrotron heater supply, a remote control panel and a protection circuitry.

The equipment will be integrated into a free electron laser system to be located and operated by scientific and technical personnel at LLNL. The equipment will be designed to withstand momentary arcs and full short circuit from any output element to another and/or to ground. Special attention will be paid in the protection scheme to assure that neither the equipment nor the load is harmed due to overloads.

The instrumentation in the control panel must display accurate and readable readings so that the operating parameters of the Gyro-BWO may be duplicated.

The safety of personnel working with the voltages involved is of paramount importance. All access panels or doors must be interlocked and a shorting device be actuated to protect personnel. Construction will be in accordance with good commercial practices, with reliability and serviceability as the prime factors. All circuit breakers, fuses and line cords must be U/L approved and power distribution must comply with local and national electrical codes.

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FIGURE B1. GYRO-BWO POWER SUPPLY SYSTEM BLOCK DIAGRAM

1.0 GENERAL SYSTEM REQUIREMENTS

1.1 PRIMARY POWER REQUIREMENTS

A main primary power circuit breaker 208 V, 3-phase 30 A will be provided.

The power supply will be designed to operate from a standard 208 volt $\pm 10\%$, 60 Hz, 3-phase, 4-wire, 10 kVA power source. All fuses and circuit breakers will be easily accessible to the operator. Special attempts will be made to keep the 3-phase lines balanced as to loading.

Running Time Meter: A nonresettable running time meter will be provided on the front of the equipment. The running time meter will be in operation whenever the high voltage has been turned on.

A large mushroom "Emergency off" button will be provided. The button will be clearly marked and located for easy access. Pressing this button will turn off all power in the test set by either dropping out the primary circuit breaker or a primary contactor.

1.2 FUSE AND CIRCUIT BREAKER PROTECTION

Each circuit of the unit, which is separable at the primary power input level, will be independently protected by fuses or circuit breakers.

Fuses and circuit breakers will be mounted on the front panel of the unit, will be logically grouped, and will be of the fault-indicating type. Unless otherwise specified, all fuses or circuit breakers will be clearly labeled with their function.

1.3 BEAM POWER SUPPLY

The beam power supply will be powered from a 208V, 60 Hz source $\pm 10\%$ output -HV is continuously variable 0-80 kV, H.V. return insulated for 15 kV minimum in respect to ground. The power supply will be capable of delivering the peak current and voltages specified and will provide the regulation and stabilities required. Stray capacitances associated with output connecting cables, grid pulser deck, and Gyro-BWO tube are budgeted at 1000 pF, 350 pF and 150 pF respectively.

Included with the regulated beam supply will be an electronic crowbar. Its function is to limit fault energy into the Gyro-BWO tube or the rf output structure and to maintain a virtual short circuit at the H.V. output past the point of primary circuit breaker opening. A bleeder and a shorting switch are also required to discharge all energy stored within 10 seconds max. of turning off (H. V.).

The cathode voltage will be continuously adjustable over the entire specified range. In addition, the output voltage will be required to linearly slew at the specified rate between any two points within the operating range.

1.3.1 Electrical Specifications

- A. Cathode Voltage Range: 60–80 k
- B. Cathode Current Range: 4–6.5 A peak
- C. Pulse Voltage Stability: $\pm 0.5\%$ from pulse-pulse and within pulse including ripple, droop, under- and overshoot (0.2% goal) not counting voltage slew change
- D. Cathode Voltage Slew Rate: 1 kV/ms, (1.5 kV/ms goal)
- E. Cathode Pulse Width: 0.1 μ s – 0.5 μ s flat top (1.0 μ s goal, optional)
- F. Pulse Repetition Frequency: 7 kHz (20 kHz goal, optional)
- G. Pulse Train Duration: 5 sec. (cw goal, optional)
- H. Max Duty: 1% (5% goal, optional)
- I. Rise and Fall Times: $\leq 1 \mu$ s, 10–90%
- J. Monitoring
 - Voltmeter: 0–199.9 kV, 3 1/2 digit 0.1% overall accuracy.
 - Current Meter: 0–199.9 mA, 3 1/2 digit current meter 0.5% overall accuracy
- K. Viewing
 - Cathode Voltage: A capacitive divider will be used to view cathode pulse amplitude. This divider will have a ratio of 10,000:1, with an accuracy of 1%
 - Cathode Current: A current transformer will be incorporated to view cathode current. This transformer will have a ratio of 0.5 V/A accuracy $\pm 1\%$

1.4 GRID PULSER

The grid pulser is made up of two units – the pulse deck and the control head. The pulse deck floats at cathode potential and the control head is at ground. All controls and monitoring signals are isolated through fiber optic links. Figure B-2 is a simplified grid pulser diagram. Note that the compensated grid divider not only sets the ratio of the control grid to focus grid voltages and cathode but also optimizes the pulse leading and trailing edges.

In order to control the ringing and overshooting normally associated with a fast-pulsed system, the grid pulse deck will be closely coupled to the corresponding gyrotron elements. Upon further definition of the gyrotron mount and environment, the pulse deck's physical details will be determined.

The grid pulse top amplitude will be continuously adjustable over the entire specified range. In addition, the output voltage will be required to linearly slew at the specified rate between any two points within the operating range.

1.4.1 Electrical Specifications:

- A. Control Grid Bias Voltage Range: -10V to -750V, continuously adjustable
- B. Control Grid Pulse Amplitude Voltage Range: 50V above bias voltage to +750V, continuously adjustable
- C. Bias Voltage Regulation: Plus or minus 1V no load to full load and plus or minus 10% line change. Ripple less than 1.5V RMS excluding overshoot
- D. Pulse Top Regulation: Plus or minus 1V no load to full load and plus or minus 10% line change
- E. Maximum Load Current: 100 mA peak current, 1 mA average current
- F. PRF: 7 kHz (20 kHz goal, optional)
- G. Pulse Width: 0.1 μ s to 0.5 μ s (1.0 μ s goal, optional)
- H. Duty: 1% (5% goal, optional)
- I. Rise Time/ Fall Time: Less than 1 μ s 10% to 90% of pulse amplitude for load capacity less than 100pf

- J. V Focus – V Control Ratio: Normally 4:1 $\pm 2\%$ (goal $\pm 1\%$) settable from 3:1–5:1
- K. Slew Rate: The grid voltage will slew at the same rate as the cathode voltage

1.5 HEATER SUPPLY

The gyrotron heater will be energized from a regulated 60 Hz sine wave power source; the heater element is at cathode potential; a low capacity (≤ 30 pF) heater transformer will isolate the high voltage and will be immersed in mineral oil (Shell Diala X or equivalent). Figure B-3 is a simplified diagram of the heater supply.

1.5.1 Electrical Specifications:

- A. Voltage: Continuously adjustable from the control panel. 0–15 Vac, isolation 100 kV, 30 pF
- B. Current: 5 Aac minimum with $\pm 5\%$ regulation
- C. Metering: RMS voltage and current 2% accuracy, 3 1/2" digital LED display with U/C and O/V settable trip 0-full scale
- D. Time Delay: Nom. 10 minutes. An adjustable 0–30 minutes time delay will be provided to allow for tube warm-up, with a current-limited ramp start. During this time delay period the beam supply will be inhibited

1.6 CONTROLS AND PROTECTION

A 19" rack will contain all the controls including primary controls, H.V. controls, digital interlock and crowbar controls, grid control and heater controls, pulse synch and viewing circuits, metering and status indicators. The H.V. and heater control with their respective metering will be on a common 19" panel. A fault latching interlock system will be used with the following inputs and indicators as a minimum

1. Cathode Over Voltage	Over Current
2. Grid Focus	Over Current

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FIGURE B3. GYRO-BWO HEATER POWER SUPPLY SIMPLIFIED DIAGRAM

3. Grid Control Over Voltage	Over Current
4. Body	Over Current
5. Vac Ion Pump	Over Pressure*
6. Magnet	Under Current*
7. Water	Low Flow*
8. Oil Cooling	Over Temp*
9. Arc Detector	ARC*
10. Raw DC	Over Current
11. Pulse Deck	Ready
12. Pulse Bias	Under Voltage
13. AC Prime	Over Load
14. Access Doors	Open
15. External Interlock	Open*
16. Cabinet Fan	Low Flow
17. Crowbar	Fault Reset
18. Heater	Over Voltage/ Under Current
19. Heater Time Delay	Time Out
20. AC Phase	Unbalance/Loss
21. Spare	
22. Spare	
23. Spare	

* Indicates conditioned logic signal provided by others.

The system turn-on sequence is as follows:

1. Primary Power (all circuit breakers on)
2. Heater Supply On
3. Bias On
4. Complete Heater Time Delay
5. Clear Interlock String
6. Beam Supply On and Undervoltage Clear
7. Grid Pulse On

Indicator lamps: The following indicator lamps will be provided as a minimum.

	<u>Color</u>
1. H.V. Off	Blue
2. H.V. Ready	Green
3. H.V. On	Red
4. Filament Power On	Green
5. Gyro Heater Zero Start	Amber
6. Gyro Heater On	Red
7. Gyro Heater Time Delay	Amber
8. Grid Pulse On	Red
9. Grid Pulse Ready	Green
10. Any interlock Not Cleared	Amber
(each interlock has a separate indicator)	

Prevent turn-on of grid pulse and beam supply

- Any door or easily removable side panel is open or removed from the unit
- An external interlock is open
- Heater time delay timer has not completed its cycle
- Fuse in primary circuit is open
- System air flow not sensed
- System water flow not sensed
- Input phase failure
- Beam Overcurrent
- Heater Overvoltage
- Crowbar Interlock
- Beam Zero Start
- AC Overload
- Magnet Undervoltage
- Magnet Overvoltage
- Magnet Undercurrent
- Body Overcurrent
- Gate Overvoltage
- Bias Undervoltage
- Arc Detector

Prevent turn-on of grid pulse only:

Beam Undervoltage:

For each of the conditions 5.1.4.1 through 5.1.5.1, amber indicator lights will be provided to indicate which fault condition has occurred. The lights will remain "On" until reset. Each fault will indicate and hold separately and simultaneously.

Door and panel interlocks will be capable of manual defeat only when doors and panels are removed or opened on the unit.

Electronic Crowbar:

Maximum effort will be expended to reduce the fault energy delivered into the load. However, it is unlikely that an arc during the pulse could be interrupted within the $1/2 \mu\text{s}$ pulse width. Nevertheless, there is an impetus to limit the rate of rise of current as well as the peak current due to an arc. The rate of rise of current should be limited close to $1 \mu\text{s}$ and peak current not to exceed 1,000 A.

Cooling:

The unit will be designed for forced-air cooling of the series regulator tube (if it is used). An interlocked air circulation fan will be incorporated to maintain cabinet air circulation. All fans will be selected and located to minimize noise level. Air cooling for the pass tube will be interlocked to prevent application of tube filament power in the event its cooling air is inhibited.

The grid pulser and associated cathode potential components will be located in close proximity to the gyro gun mount. Details of this interface will be determined at a later date in close cooperation with LLNL.