A novel injection-locked amplitude-modulated magnetron at 1497 MHz

Final Technical Report for the Phase I STTR Project Starting 2/17/2015, ending 12/15/2015

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PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY
Work Performed Under grant DE-SC0013203

ABSTRACT

Thomas Jefferson National Accelerator Facility (JLab) uses low efficiency klystrons in the CEBAF machine. In the older portion they operate at 30% efficiency with a tube mean time between failure (MTBF) of five to six years. A highly efficient source (>55-60%) must provide a high degree of backwards compatibility, both in size and voltage requirements, to replace the klystron presently used at JLab, while providing energy savings. Muons, Inc. is developing a highly reliable, highly efficient RF source based upon a novel injection-locked amplitude-modulated (AM) magnetron with a lower total cost of ownership, >80% efficiency, and MTBF of six to seven years. The design of the RF source is based upon a single injection-locked magnetron system at 8 kW capable of operating up to 13 kW, using the magnetron magnetic field to achieve the AM required for backwards compatibility to compensate for microphonics and beam loads. A novel injection-locked 1497 MHz 8 kW AM magnetron with a trim magnetic coil was designed and its operation numerically simulated during the Phase I project. The low-level RF system to control the trim field and magnetron anode voltage was designed and modeled for operation at the modulation frequencies of the microphonics. A plan for constructing a prototype magnetron and control system was developed.

NARRATIVE SECTION

A novel injection-locked amplitude-modulated magnetron at 1497 MHz

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Project Overview

As drop in replacements for the klystrons at JLAB, 80+% efficiency magnetrons with injection locking and amplitude modulation will not only reduce JLAB's operating costs, but also the acquisition costs of their power sources. The gain achievable with phase locking has reached 30 dB as shown by a number of researchers [1,2,3]. In this project we will build and test a prototype 1497 MHz magnetron and its control system, which use an additional trim magnetic circuit to provide amplitude modulation (AM) to control microphonics in superconducting RF cavities.

The optimization of the magnetron design is based upon two elements: the flux path of the magnetic field and Qext. The lower the Qext, the broader the injection locking bandwidth, but too low and the magnetron will not oscillate. For the magnetic field to be able to achieve amplitude modulation for the suppression of microphonic effects, AM rates of 50-1000 Hz are expected. These rates will create eddy currents in the conductors that will be minimized by the design and use of materials in the magnetic circuits.

During the first year of the Phase II, 1497 MHz magnetrons will be built and tested. During the second year, the integration of the RF drive circuitry including injection locking and amplitude modulation will be tested with superconducting RF cavities as a load.

Significance and Background Information, and Technical Approach

The magnetron is the RF device source that best meets the requirements of a low-cost, high-efficiency RF source for accelerators used in physics research and other applications. As our Phase I work indicated, there are some modifications that need to be implemented for the magnetron based RF system before the advantages of low cost and high efficiency can be utilized. We propose in this Phase II work to complete those modifications in the design and prototype development of a 1497 MHz magnetron, as well as construct and test the prototype feedback circuitry modeled in our Phase I work.

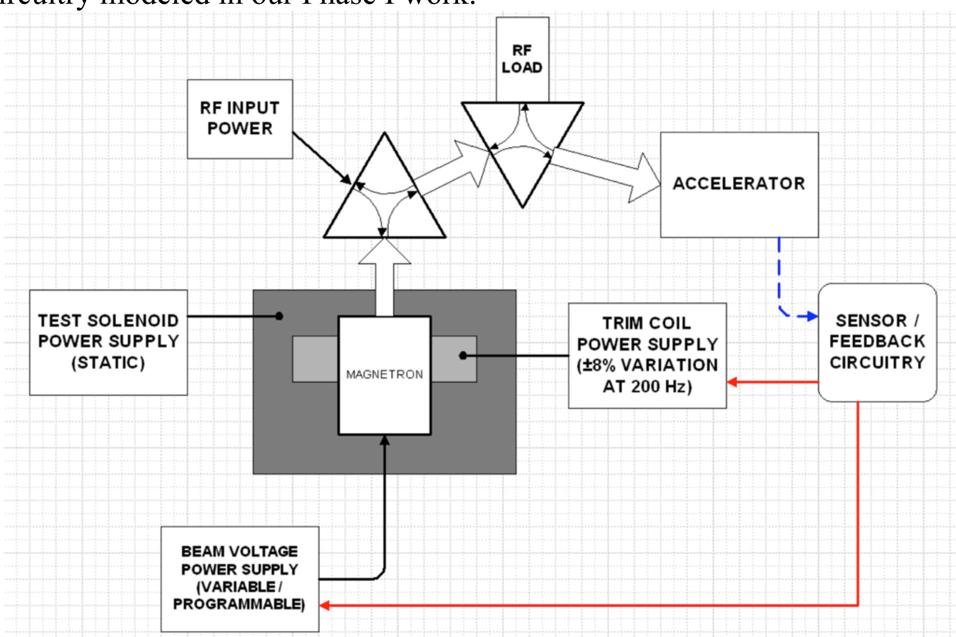


Figure 1: Block diagram of the fundamental components of the injection locked AM magnetron.

The magnetron RF system is built upon three major components that are identified in Figure 1:

- Injection locking with an input power source and circulator
- A trim coil and related magnet design
- Feedback circuitry.

General State of the Art

Injection Locking

Injection locking has been demonstrated to work on a standard magnetron with a 30 dB gain between the output of the magnetron and the input power required to injection lock [4]. In 1991 phase locked magnetrons were used to drive an RF cavity with a moderate Qo of 5100 at 8.964 GHz with 13 dB gain [5]. An injection locked magnetron was used to drive an SRF cavity at JLab using feedback circuitry to maintain stability of less than 0.8° r.m.s with 27 dB gain [6].

To reduce the noise and achieve +30 dB gain, the DC filament voltage was adjusted to operate in the space charge limited regime. Additional noise reduction was achieved by reducing the ripple of the switch-mode power supply. The state of the art 30 dB gain is a perfectly adequate level making the power for the driver of a 13 kW magnetron about 15-20 watts depending on the insertion loss of the circulator and associated hardware.

Trim coil and related magnetic circuit design

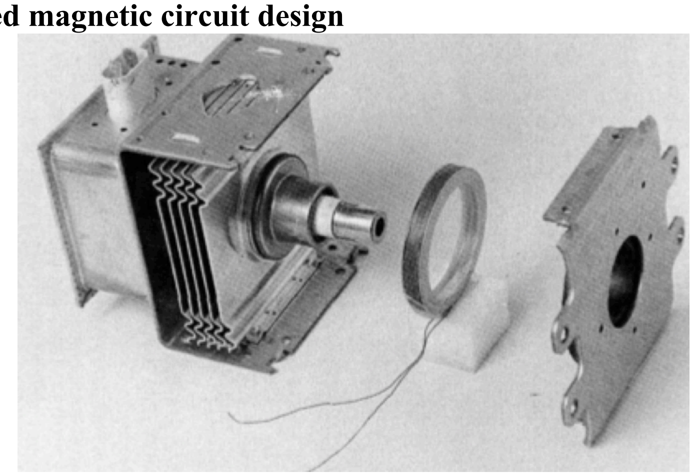


Figure 2: Implementation of a “buckboost” coil for achieving high gain in the phase-locked circuitry of a microwave oven magnetron [4]

Trim coils and flux straighteners are not standard to magnetron designs. Trim coils have been used to improve noise and stability in magnetrons as shown in Figure 2. Flux straighteners or other methods for improving the flux path for electron interaction with various structures is well known in the microwave tube industry. This PI has had that experience with low-noise TWTs.

Feedback circuits in magnetron RF systems

The techniques used to improve noise and stability in magnetron systems driving SRF cavities have been studied primarily at JLab as discussed above.

The recent introduction of Fermilab to the use of magnetrons in driving an SRF cavity [7] is primarily based on an alternate modulation scheme where sidebands are created by the modulation and subtracted from the output power of magnetron thus creating a modulated output. The sidebands are rejected by the narrow bandwidth of the SRF cavity and sent to a load by the third arm of a circulator similar to that shown in Figure 1. Under this technique the magnetron is operated at full power and efficiency, yet the overall efficiency of the system is degraded. If modulation of the output power is on the order of 3 dB, then the efficiency of the system is reduced by 50%. What was once an 80% efficient RF system is now 40% efficient. (Based upon efficiency, the better approach is obvious)

Technical Approach as determined by the Phase I work

In the Phase I work, we focused first on the magnetron's magnetic circuit based on the study of the critical features of the circuit and second on the low Qext of the magnetron which has been identified in a number of research papers and reports as critical to the bandwidth of injection locking. A summary of the details of this work is discussed below.

In Phase II, in addition to demonstrating the magnetron design modifications needed for the trim circuit to control amplitude modulation, we will also develop the feedback/feedforward circuitry that will adjust the anode voltage to maintain system efficiencies of greater than 80%.

Magnetron Design

Trim coil and related magnetic circuit design

The fundamental criterion for AM of the magnetron output power is the modulation of the electron density in the spoke of current in the interaction region. This can be accomplished in two ways: anode voltage and magnetic field. We've designed an anode that meets the requirements of operating at 1497 MHz as shown in Figure 3 and studied its impact on B_z.

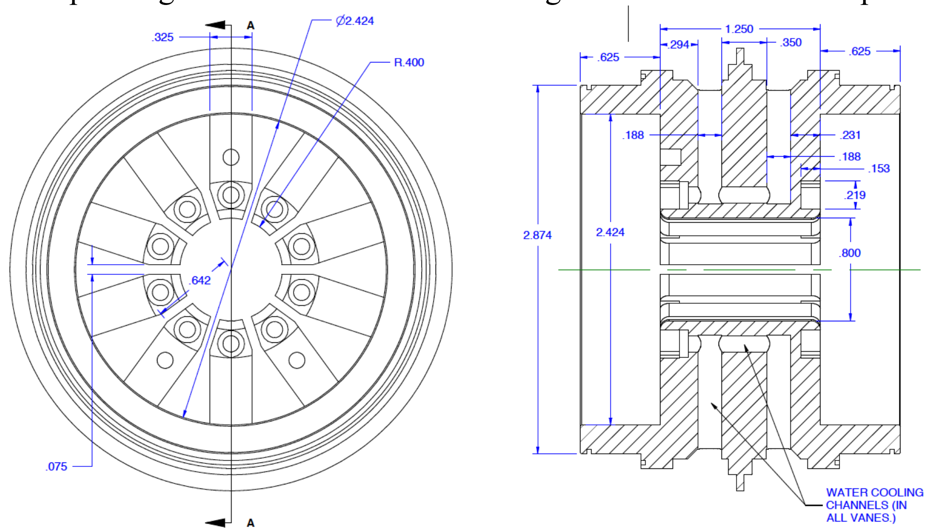


Figure 3: 10 vane anode for the 13 kW, 1497 MHz magnetron with associated cooling channels.

To model the impact of eddy currents on the magnetic field and subsequent heating issues if any, the magnetic circuit was modeled in Opera (and Comsol). The circuit used is shown in Figure 4.

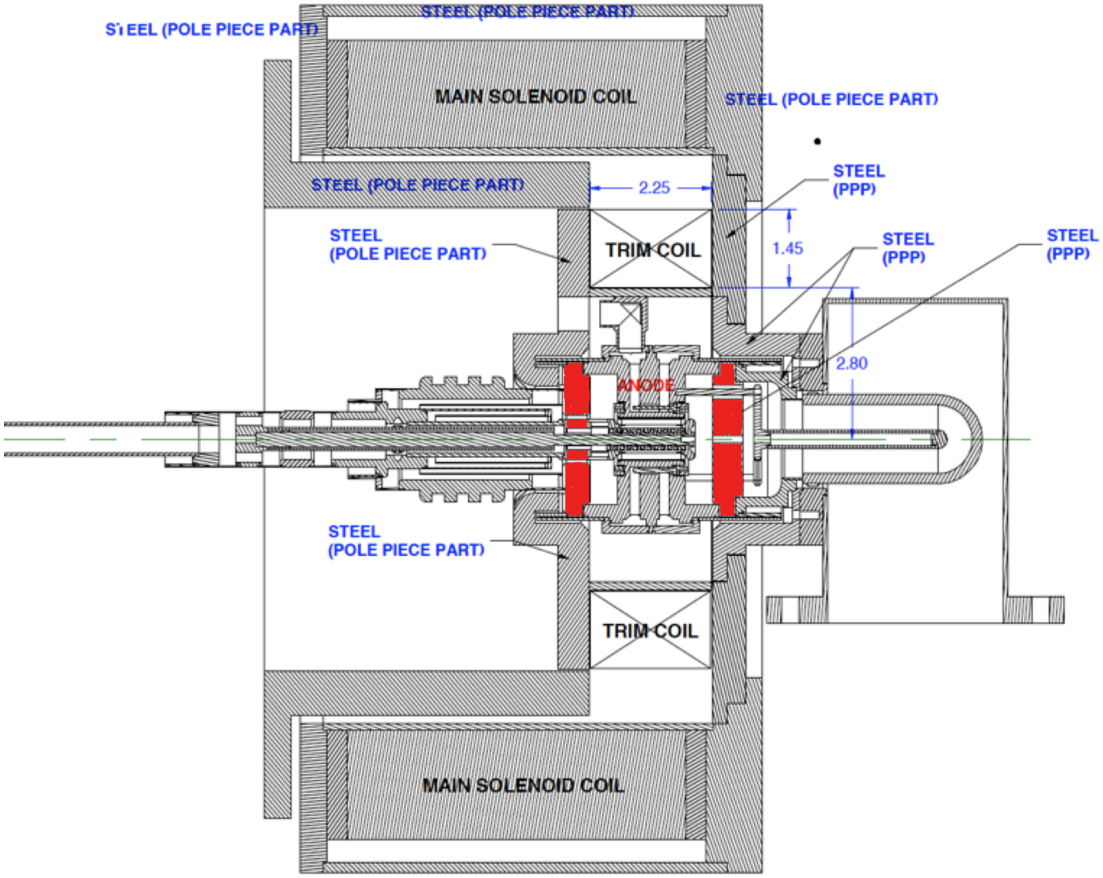
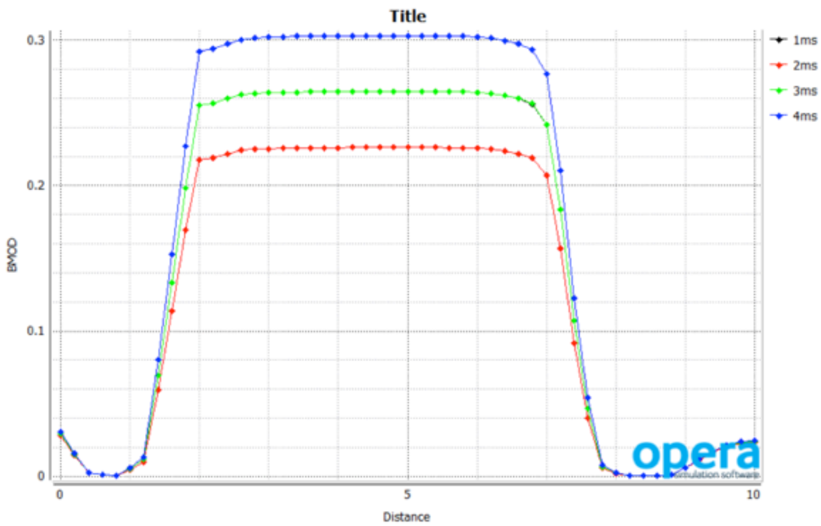


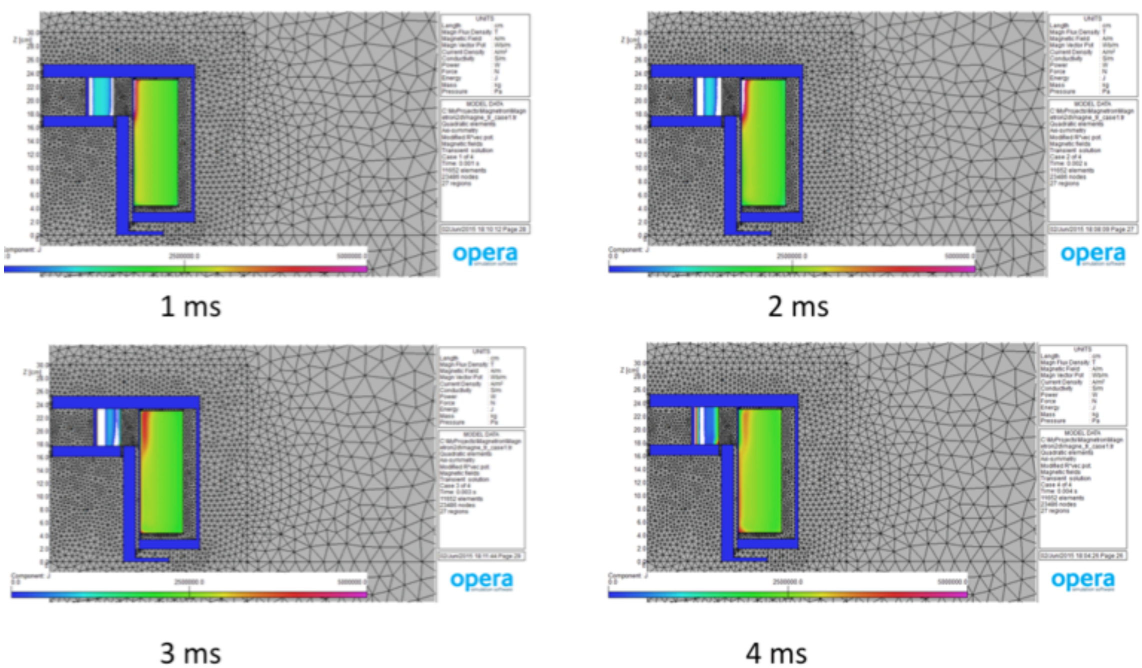
Figure 4: Magnet configuration used for eddy current calculations. The red parts are the built-in iron pole pieces which are part of the magnetron vacuum envelope in standard designs.

This configuration is based upon the use of a main solenoid already in hand with the construction of a "trim coil" as shown in Figure 4. The main solenoid produces the necessary 2500 gauss in the interaction region and the trim coil produces 10% of that or 250 gauss for modulating the current in the spokes of the electron cloud. One set of studies consisted of 2D models of the axial field in the interaction region of the magnetron and on the main solenoid coil from variations in the trim coil at 250, 300, 350 and 1000 Hz without the copper of the anode. Some of the results are shown in Figure 5. They indicate there is some skin effect on the main coil and transients on the field in the interaction region. Both of these suggest the need for further improvements in the magnetic design of the magnetron. Figure 5(a) and (b) were for the iron structure alone, the copper of the anode was then added in Figure 5(c). The time constant for the field on axis resulting from the trim coil is shown in 5(c) and calculated to be 8.4 ms.

2D Transient with Cosine Drive; Field on Axis in Anode Region at Various Times



(a)



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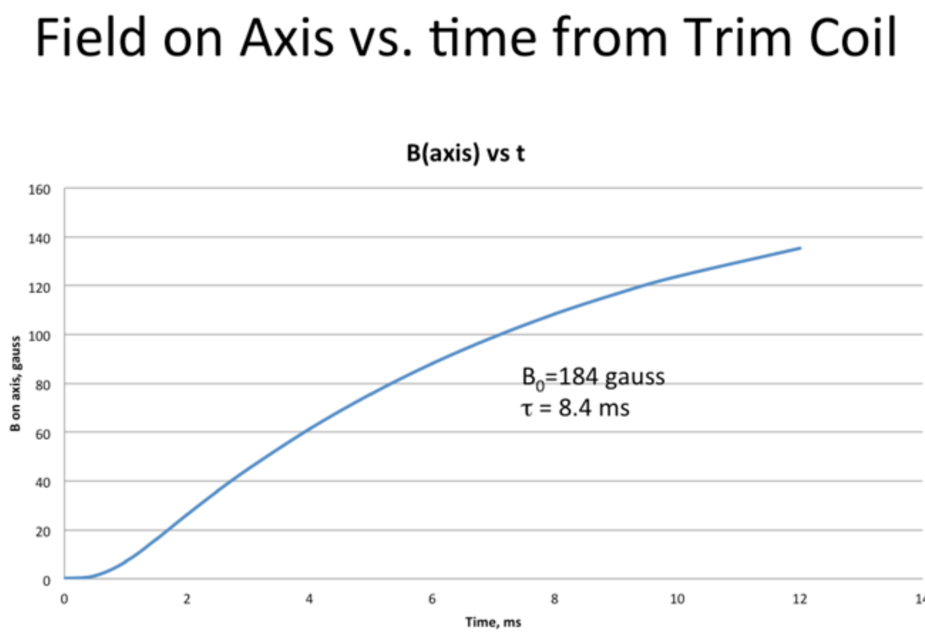


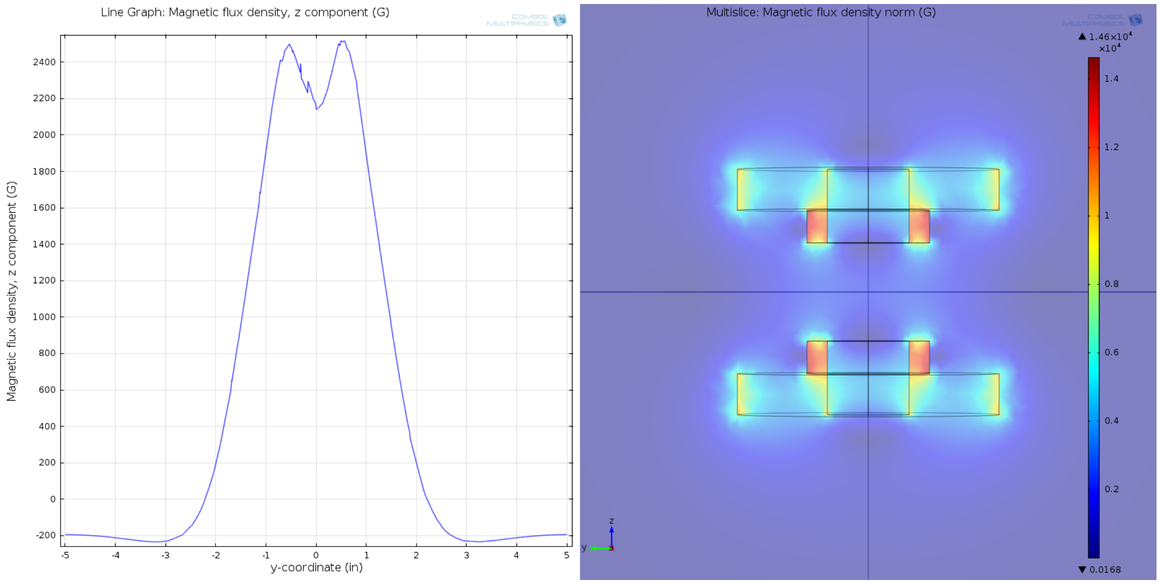
(c)

Figure 5: Transient calculations with 250 Hz drive in the trim coil for (a) the field in the interaction region without copper anode and (b) impact of the trim coil fields on the main coil. And (c) time constant of field on axis from the trim coil with copper anode present in the simulation.

As a result of these studies in our Phase I, changes to the magnetic circuit of the magnetron will be implemented in Phase II. These changes are two fold: 1) implementation of laminated iron in the magnetic circuit, and 2) changes to the profile of the iron pole piece in the vacuum envelope of the magnetron.

The profile of the iron pole piece shown in Figure 4 produces a nearly uniform 2500 gauss from the centerline to the outside edge of the anode. Adding a tip to the pole piece concentrates the field in the interaction region where it is actually used as shown in Figure 6. This type of change reduces the field in the anode region that is not necessary to the operation of the magnetron by about 50%.

Additional changes to incorporate the use of laminations in the iron will further reduce the impact of eddy current on the delivery of the flux to the interaction region. Laminated iron cores are standard techniques for audio circuits and the technology is quite advanced for insulating the less than 1 mm thick iron sheets. During the Phase II program, laminations will be incorporated into the magnetic circuit design using commercially available materials such as those from Wiltan Magnetic Components (www.wiltan.co.uk).



(a) (b)

Figure 6: Field enhancement in the interaction region with the addition of "ears" on the pole pieces.

In the commercial production of this injection-locked AM magnetron it is unlikely that the main magnetic field would come from a solenoid, but from permanent magnets. Permanent magnets have been used with magnetrons to lower the input DC power to systems [8]. We explored the likelihood of using permanent magnets in this 1497 MHz magnetron.

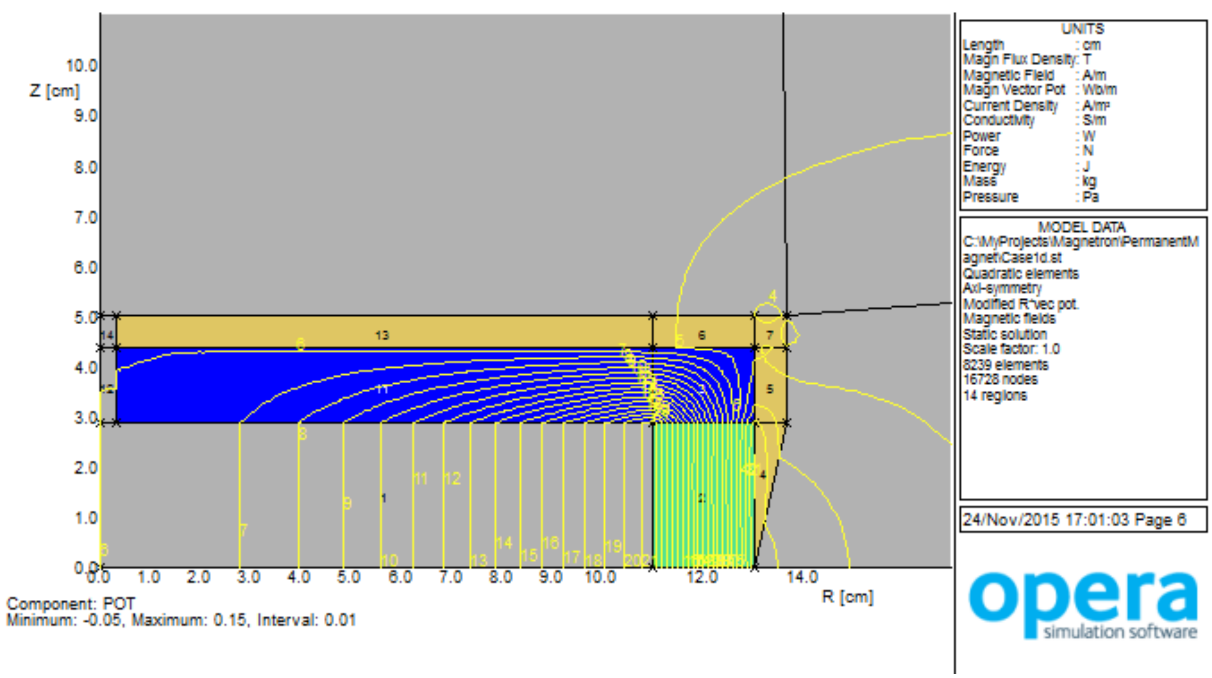


Figure 7: Magnet configuration using permanent magnet cladding to reduce the external magnetic field

Figure 7 shows the Opera calculations with a permanent magnet providing 2500 gauss. The permanent magnet material used is neodymium iron boride ($Nd_2Fe_{14}B$). The neodymium permanent magnet material is quite temperature dependent and is generally used in conjunction with a temperature compensating material such as Ni-Fe. The design requires permanent magnet blocks in a circular configuration. While this is a preliminary study, the proposal to use permanent magnets in the commercial design of the injection-locked AM magnetron looks feasible.

Locking Bandwidth and Q_{ext}

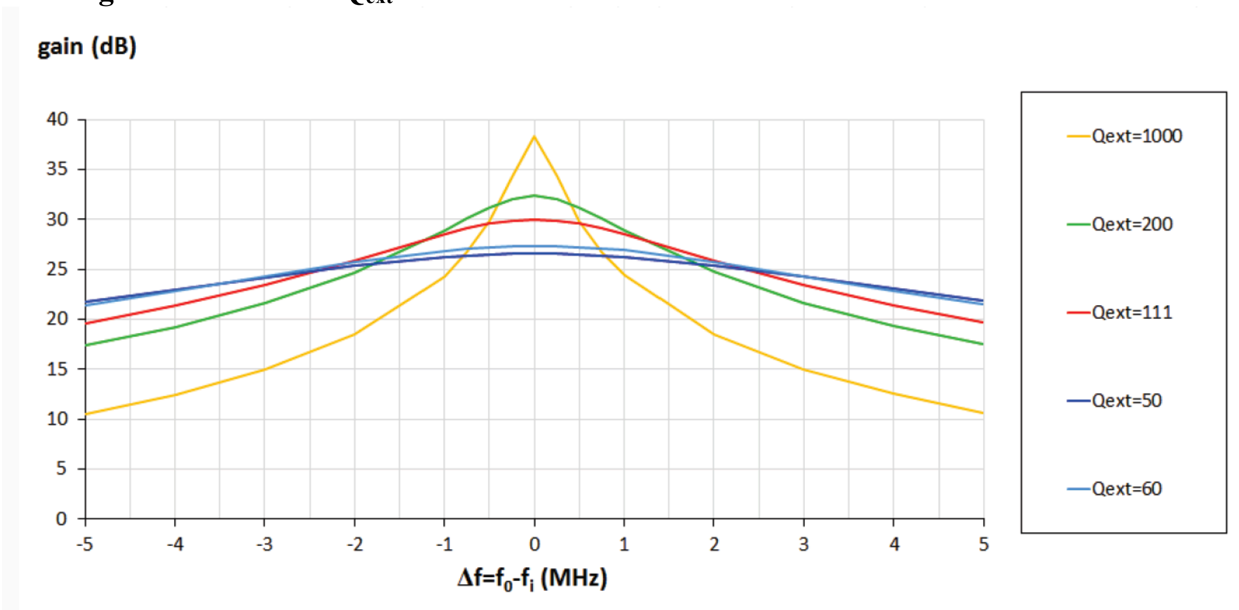


Figure 8: Locking bandwidth for a 350 MHz magnetron as a function of Qext.

Figure 8 shows the calculations for Qext and gain for a 350 MHz magnetron Muons, Inc is building and testing for Niowave. As Qext is lowered, the system gain for a phase locked magnetron is lowered, at the same time the locking bandwith increases. In the Phase I we have designed a simple method for increasing the locking bandwidth by adjusting the VSWR of the magnetron load. This method has been used by others and has shown to work well [9]. In our system, the reflection coefficient of the load is controlled by a simple waveguide H plane iris before the first circulator shown in Figure 1. The only concern of this approach is the increased heat load due to the reflected power. As shown in Figure 8, the tradeoffs between gain and bandwidth are important considerations when lowering Qext, and these tradeoffs will be measurable during Phase II on the 1497 MHz magnetron we will be building.

The tradeoffs between the amount of reflected power and the heat load in the anode cooling system will also be determined during Phase II when the completed magnetron is tested into the circulator. It is only then that the impact of the load VSWR and thermal effects can be fully optimized. (The cooling system designed and studied in the next section takes into account the worst-case situation of the magnetron operating into a short with 13 kW dissipated in the anode.)

The Qext of the magnetron has been studied in this Phase I with regard to the means to lower it in the magnetron design. The design element chosen by our design will be the manner in which the antenna is attached to the vanes. As shown in Figure 9, the antenna has three connections to three vanes of the ten vanes. The connection circle diameter the three arms of the anode support structure make on the vanes is one means for controlling the Qext of the magnetron.

Shown in Figure 10 **Error! Reference source not found.**is a graph of the Qext versus connection diameter referenced to the center of the vane with respect to the center line of the magnetron. (It is important to note that a magnetron with a Qext below 80 will most likely not oscillate; however, in our system to be tested in Phase II, this may change based upon the load VSWR the magnetron will be operating into.) The location of the connections is made before the tube is baked out. The vane-strapped anode, which will have gone through a number of brazing operations for the straps and water cooling system, is connected to the antenna support structure in a test fixture and the measurements made of the frequency and Qext. Typically this is done a couple of times before the final holes are drilled to attach the legs.

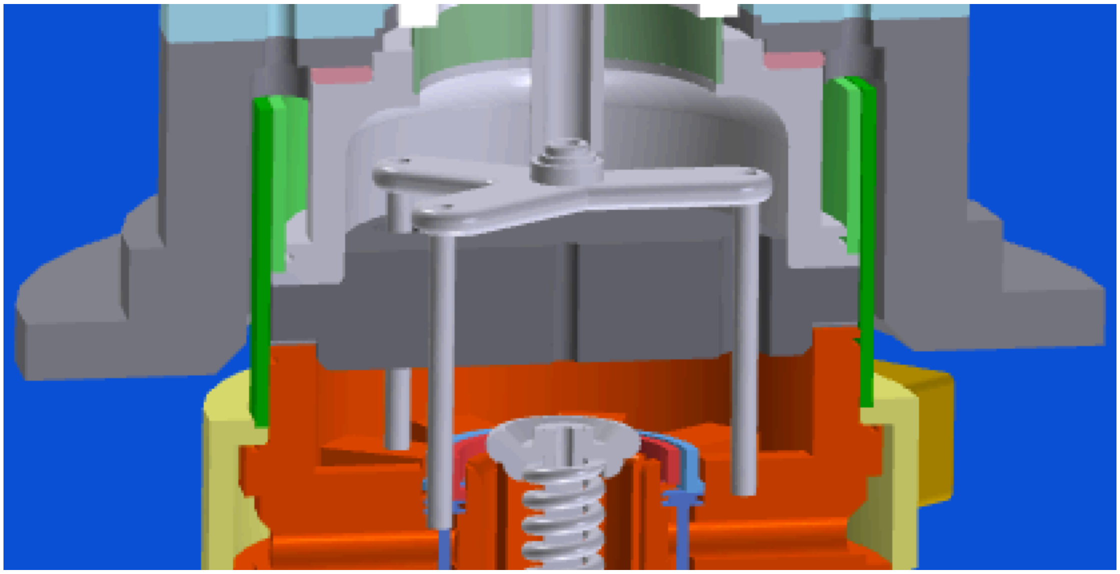


Figure 9: Cutaway of the 1497 MHz magnetron design showing the details of the antenna connection through the top pole piece to the vanes.

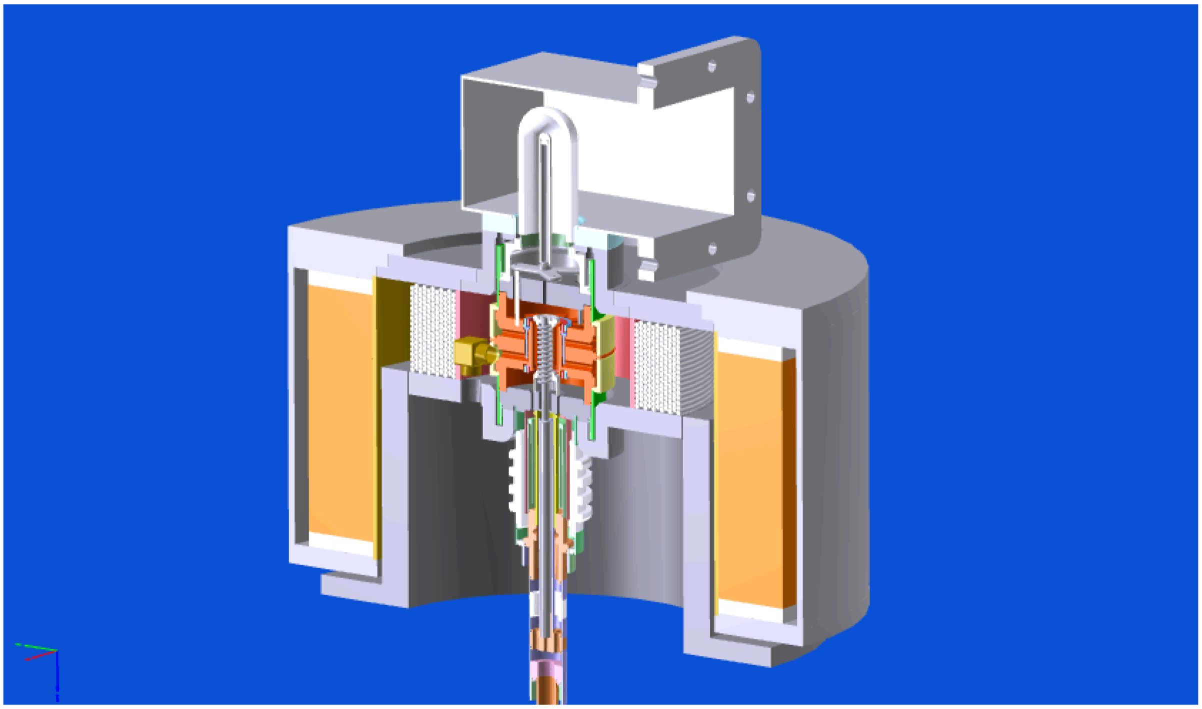


Figure 9b: Section view of the full magnetron assembly

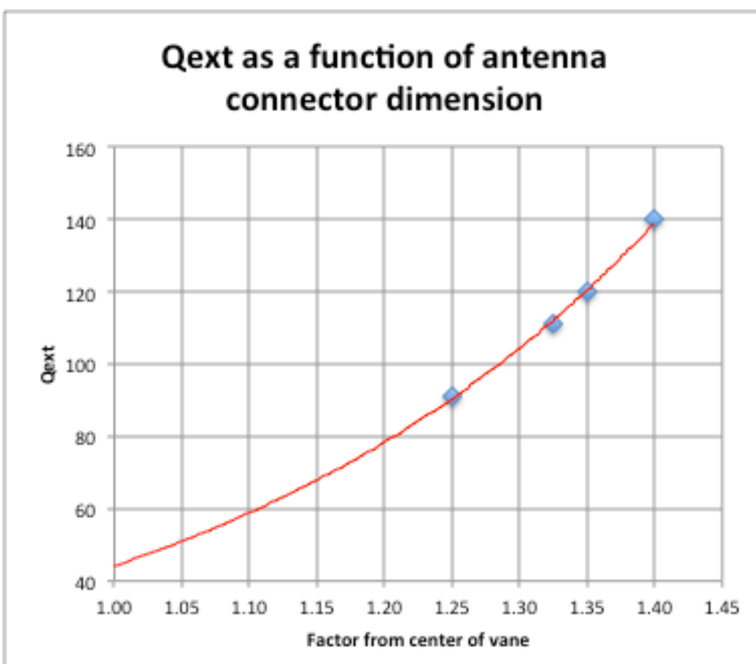


Figure 10: Calculations of the Qext of a magnetron as a function of where the antenna connections are with respect to the center-line of the magnetron. (1.0 is the radial center of a vane.)

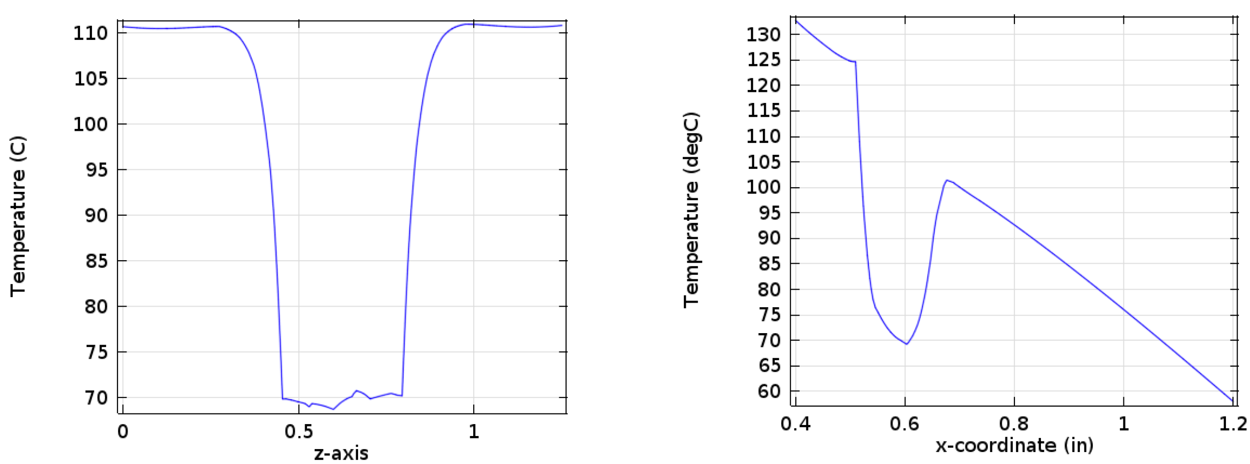
Cooling Design of the Magnetron

It is a ten vane anode. This means that a 13 kW magnetron operating at 80% efficiency sends 2.6 kW to the vanes or 260 watts per vane. But this is a small percentage of the heat the vanes see. The greatest source of heat is the filaments that operate in the range of 900 to 1100 C. That heat is transferred to the vanes by radiation. If there were no internal cooling of the vanes, they would operate at approximately 500C due to radiation heating from the filaments with an interaction gap of 0.1 in. Doubling the gap reduces the temperature due to radiation by 100 C. The temperature rise due to 260 watts per vane (located at the tip due to electron bombardment) is 54 C. Again, these are calculations without water-cooling.

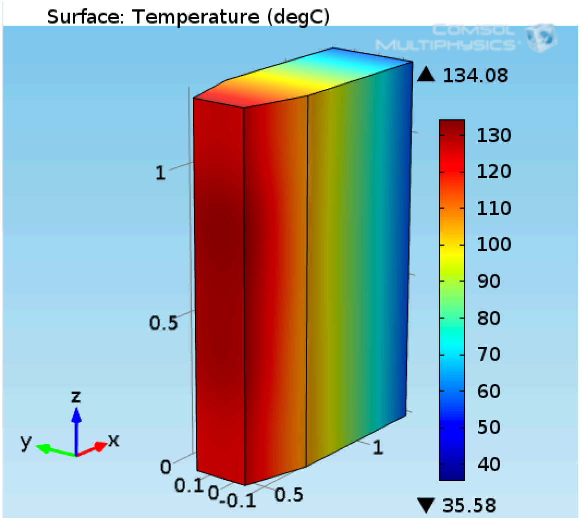
To evaluate the design with water-cooling, a model was made in Comsol as shown in Figure 11. We also included power dissipated in the vanes due to reflection from the load VSWR. In the example shown below, 200 watts per vane is the heat flux treated in this way. This represents a reflected power of 2 kW due to a VSWR of about 2.5:1 when the magnetron is operated at 13 kW.

Other sources of heat include the power loss in the iron pole pieces and antenna. At 13 kW, the antenna is not required to have water-cooling, while the iron pole pieces will be cooled on their perimeter. The stem of the magnetron, which includes the high voltage ceramic and fittings for the filament supply, is another heat source due to the resistive losses from the heater current and choice of materials to support the filament which have high resistance such a molybdinum. The cooling for this section of the magnetron is convection.

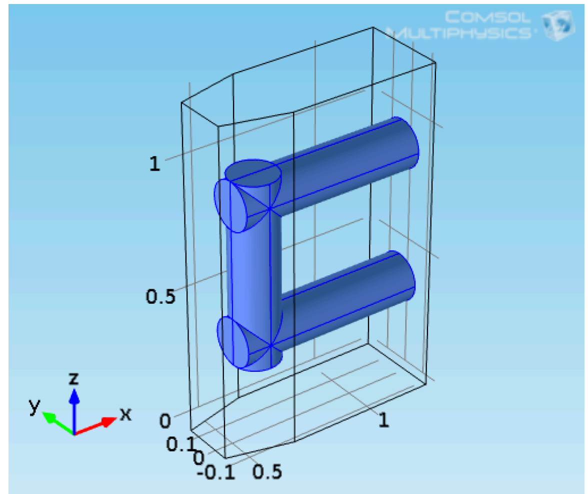
To summarize: 260 watts is dissipated on the nose of the vane from electron bombardment of the spent beam, and worst case 200 watts are dissipated over the entire surface area of the vane as a results of reflected power from an output VSWR of 2.5:1. With these heat fluxes, the calculations indicate that the temperature of the water rises to 70 C in the vane with an inlet temperature of 37 C and a flow rate of .3 gpm per vane or 3 gpm total. This information and calculations gives us confidence in the vane cooling design with the associated water channels.



(a) (b)



(c)



(d)

Figure 11: Thermal calculation of the vane tip with water-cooling: (a) z-axis through the center of the vertical portion of the channel, (b) x-axis through the vertical center of the vane, (c) surface temperatures in C, and (d) picture of the cooling channels.

Feedback circuits in the 1497 MHz magnetron RF system

A Simulink simulation has been studied extensively at JLab to model the performance of the magnetron assuming the Vaughan analytical model that has been used extensively in the microwave tube industry for over 40 years [10]. The model is also elemental to the understanding of the CEBAF control system building on the new LLRF design specification and control diagrams for the SRF cavity with beam loading [11]. The paper just referenced (WEPWI028) was presented May 3-8 at IPAC 2015 by H. Wang, et. al. representing the JLab work done on this Phase I.

The conclusions from their paper are presented here: The magnetron can be modeled as an anode voltage controlled oscillator, the loop gain and bandwidth of the LLRF control determine the locking stability and accuracy. Table 2 in the paper lists the preliminary simulation performance data. However the characteristics of an as-built magnetron need to be measured and its amplitude control by ramping anode voltage and magnetic field need to be experimentally demonstrated. Frequency pulling by the output circuit of magnetron has not been simulated in the current model.

Table 2: Preliminary Simulink Result for C50 Cavity

Gradient (MV/m)	Loaded Q	Amp. rms error (%)	Phase rms error (deg)	PID gains
10	8e6	0.7	0.2	100-20-0
6	8e6	0.3	0.2	100-40-0

Figure 12: Table 2 of the work done by H. Wang at JLab [11].

Magnetic Circuit Design
Extensive modeling of the magnetic circuit showed the possibility of eddy currents negatively impacting the amplitude modulation concept. Design changes were studied to mitigate the eddy currents and reconfigure the top and bottom pole pieces inside the vacuum envelope to enhance the field in the interaction region. This is a unique design element to improve AM of the output power with magnetic field.

Magnetron Design
The magnetron design is complete. Piece part drawings which take significant time to produce are, as planned, to be done during the first three months of the Phase II.

Feedback Circuit Design
JLab has studied the feedback circuitry and the capabilities of the amplitude modulated injection locked magnetron to drive their C50 cavity with their required stability in phase and amplitude. They produced a paper in IPAC2015 which documented their results.

The Phase II Project Plan
The Phase II project plan is straightforward:
(a) Build and test the 1497 MHz magnetron designed in Phase I
(b) Build and test the magnetic circuit designed in Phase I.
(c) Build and test the feedback circuit designed in Phase I with the injection locked magnetron.

Building and testing the magnetron requires coordination and good management from Muons, Inc. The documentation of the design and required processes has already been done for the 350 MHz magnetron Muons, Inc is building. And when we say building, we mean the coordination of piece part procurement for all components as well as assembly.

Technical Objectives
The objective: successful operation of the injection locked 13 kW, 1497 MHz magnetron with AM control using feedback circuits on the anode voltage and magnetic field.

Phase II Work Plan - Magnetron
The plan is to complete the detailed drawings for the magnetron, order the parts, and build and test the magnetron. Brazing and sub-assembly builds will be outsourced to facility such as Altair Technologies in California. Other sub-assembly builds of external parts such as the magnetics and waveguide will be done at Device Technologies. Testing will be done at JLAB. The magnetic circuit will be experimented with at that time to verify amplitude modulation. The feedback circuitry will be built and tested at JLAB using the design developed during Phase I. The combination of magnetron and feedback circuitry will be tested at JLAB with 1497 MHz cavities.

It is common to build more than one magnetron of a new design to verify the manufacturing processes. We also plan to accomplish this task by ordering parts for five magnetrons and building sub-assemblies. This is standard practice because of yield issues that may arise during manufacturing. Also, it may turn out that performance is not as expected of the first magnetron, so sufficient parts and assemblies would be on hand for the building of a second magnetron with modifications. Multiple sub-assemblies also reduce lead times as testing is done at various levels of manufacturing to assure the highest quality final assembly.

Organizing the workflow is complicated by the use of various suppliers for the different types of materials used in building a vacuum tube. But the building of magnetrons is the easiest of the high-powered microwave sources because of the simplicity of design. That is why it is the most cost efficient of the microwave sources.

Work Flow - ceramics

The three basic types of materials in the construction of the magnetron require at least three different suppliers: metalized ceramics, filament, and machined copper.

Typical lead times for metallized ceramics such as AL995 (99.5% pure alumina) or AL300 (97.6% pure alumina) in small quantities can be six to nine months with the big supply houses such as Morgan Technical Ceramics (http://www.morgantechnicalceramics.com) and CoorsTek (http://www.coorstek.com) both of which provide ceramics for the microwave tube industry and have significant backlogs. For ceramics we can go to a place such as B&H Technical Ceramics (http://bhceramicsinc.com) in San Carlos, California and have them metallized at Elcon (http://elconprecision.com). The PI for this project has had extensive experience making metal-to-ceramic seals with these materials and working with both the big and small companies.

With large electric fields in the antenna region which is surrounded by the dome ceramic, as shown in Figure 4, a titanium nitride coating is often used to limit multipactor caused by the triple junction (ceramic-metal-vacuum) and high secondary yield from ceramics. We do not anticipate the need for this type of process for a magnetron delivering 13 kW at 1497 MHz.

The high voltage ceramic in the cathode stem end of the magnetron shown in Figure 4 is grooved to lower the voltage gradient along the ceramic surface so that it can operate in air and in the presence of humidity. If this is not sufficient in the magnetron package design, then potting the ceramic stem in RTV (room temperature vulcanization) silicone is performed with a material such as Dow Corning HV 1760. Typical gradients used in microwave tubes that require RTV on the ceramics is 20 to 30 kV/inch. Our design will be less than 2 kV/inch.

Work Flow - filament

Union City Filaments (http://www.ucfilament.com) is the recognized quality supplier of wound tungsten and tungsten alloys for this application. The most important issue to be minimized is sagging of the filament during operation. Union City has specialized processes to minimize the sagging through various firing processes. We will buy wound filaments from Union City with their processing. The temperature test is done in a vacuum bell jar.

The stem assembly, shown in Figure 13, is powered by a filament supply. The input power is then correlated to the temperature of the filaments as measured by an optical pyrometer. The firing time is at least 24 hours. This tests the welds to the filament, the assembly of the stem and verification that the filament does not sag.

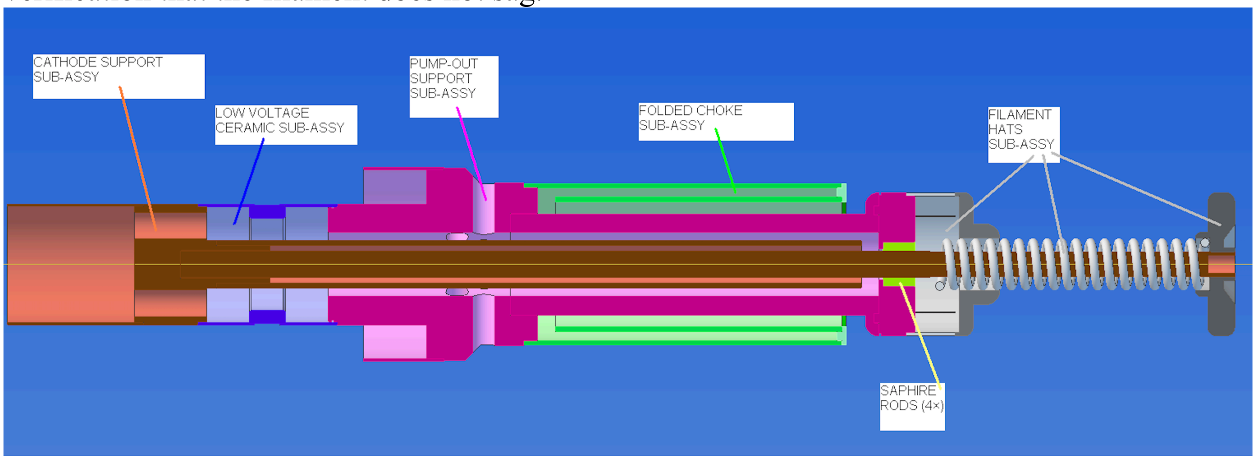


Figure 13: The filament stem assembly that is tested in the bell jar to verify temperature and anti-sag properties.

We have chosen Altair Technologies (http://www.altairusa.com) located in Menlo Park, CA to perform this test along with brazing various sub-assemblies. (Varian Associates started Altair Technologies as an outsourcing company in 1991. And this PI is very familiar with the organization and processes this company provides.)

Work Flow – machined parts

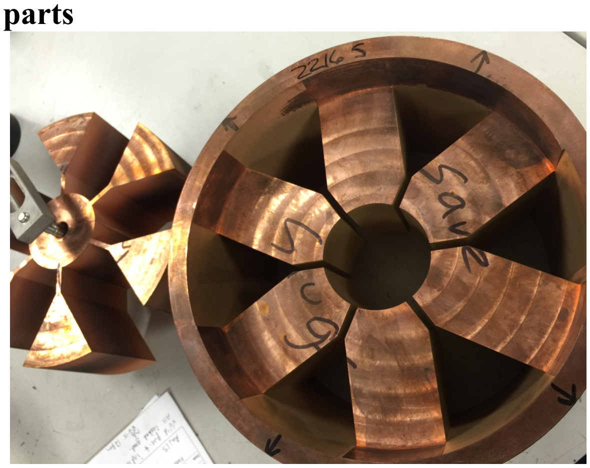


Figure 14: Example of an EDM'd anode being made for the 350 MHz magnetron Muons, Inc is building for Niowave.

Several different machine shops could do the work required to produce the parts per the drawings we will be providing. Currently we are primarily working with Device Technologies in Yorkville, Il., and Grand Island Ranch machining located in Ryde, CA. Both of these companies do major machining operations for national labs: Device Technologies for Fermilab, and Grand Island Ranch for Lawrence Berkeley Labs.

Drawing Tree

Row	A	B	J	K
1	350 MHZ MAGNETRON DRAWING TREE			
2			build operation	tests
3				
4	350MAG 082114-1_A-MAGNETRON VACUUM ASSY		weld	Bakeout 24 hrs +
5				
6		350MAG 062614-1_D-ANODE 5TH BRAZE ASSY	braze w/ nicusil 3	cold test frequency
28		350MAG 062714-5_A-DOME BRAZE ASSY	braze w/ nicoro	
36				
37		350MAG 071414-2_A-ANTENNA BRAZE ASSEMBLY	braze w/ nicoro	
41				
42		350MAG 071714-2_A-INNER PP. HV CER. WELD ASSY	weld	vacuum leak check
55		350MAG 072514-2_A-COMPLETE CATH STEM W- MOLY HATS & FILAMENT	weld (W & Moly)	Temperature
85				
86		350MAG 072414-5_A-PUMP-OUT PARTS BRAZE ASSY	braze w/ nicoro	
95				

Figure 15: Example of the Drawing Tree for the 350 MHz magnetron with six levels in the documentation.

The drawing tree example shown in Figure 15 is for our 350 MHz magnetron. It involves all the parts required to build a magnetron along with a description of the sub-assembly tests and processes required to build the assembly. There are approximately 90-100 parts that go into the vacuum envelope with about 15-20 assembly stages. Again, these numbers are relatively low for a microwave tube, and the primary reason for the low cost. A klystron for example has about 300-400 parts and about 50-75 assemblies at various stages.

Magnetic Circuit and Waveguide

The magnetic circuit designed during Phase I will be built and tested. Winding of coils will be done by a company such as Device Technologies which we have used in the past for coil development. The waveguide assembly will be built by a company such as Device Technologies.

Testing the magnetron

The magnetron, magnetic circuit, and waveguide will be assembled for final test at Device Technologies and then shipped to JLAB for testing with the power supplies and other equipment used for tests.

Phase II Work Plan – low level RF

JLAB has built and tested various components of the LLRF system required in this proposed Phase II effort. Testing the magnetron with the magnetic field trim coil to vary the output amplitude with a variety of anode voltages and currents will be performed so that the look-up tables for the LLRF can be input into the software as shown in Figure 16. Once the software is complete, the full system with programmable power supplies will be tested.

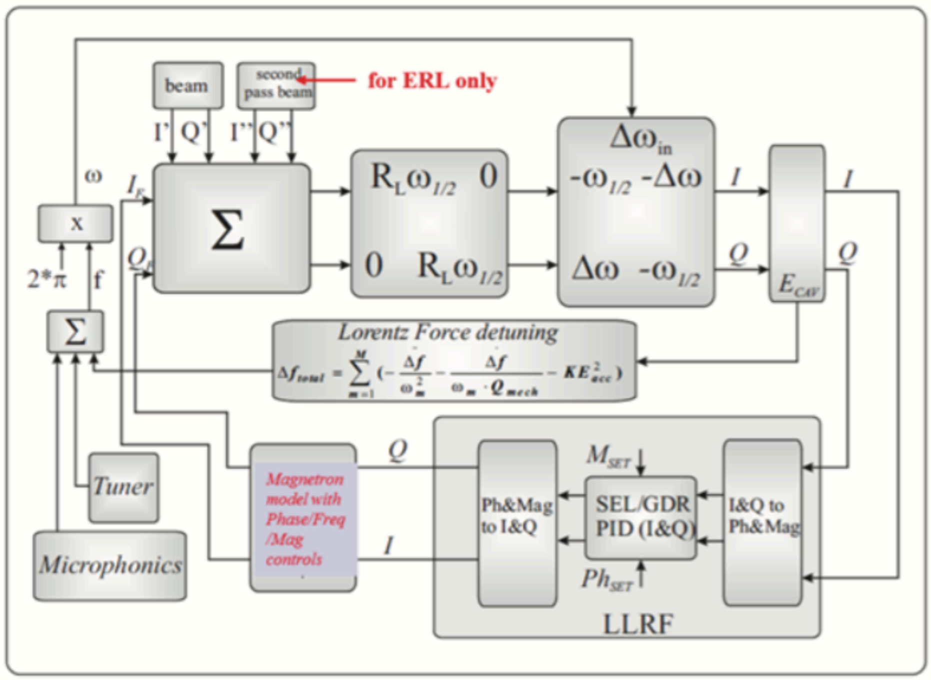


Figure 16: The system that will be built by JLAB is a subset of this system used for simulation purposes [6].

Conclusions

Muons, Inc and JLab have put together a unique team of engineers and physicists to make this project happen. Muons, Inc has the microwave tube experts in this PI and the magnetron tube experts in the consultants Tony Wynn and Ron Lentz. JLab has been creating and testing feedback systems for operating magnetrons which meet their exceptionally high standards of Phase and Amplitude stability. This team is uniquely qualified to implement a Phase II which will prove that the low-cost highly-efficient magnetron can be the power source for accelerators.

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