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INNOVATIVE MAGNETRON POWER SOURCES FOR SUPERCONDUCTING RF (SRF) ACCELERATORS*

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Abstract

A magnetron suitable for 1497 MHz klystron replacements at Jefferson Lab will be constructed and tested with our novel patented subcritical voltage operation methods to drive an SRF cavity. The critical areas of magnetron manufacturing and design affecting life-cycle costs that will be modeled for improvement include: Qext, filaments, magnetic field, vane design, and novel control of outgassing. The most immediate benefit of this project is to make SRF accelerator projects more affordable for NP and other users of SRF Linacs. One of the most attractive commercial applications for SRF accelerators is to drive subcritical nuclear reactors to burn Light Water Reactor Spent Nuclear Fuel (LWR SNF). A 1 GeV proton beam hitting an internal uranium spallation neutron target can produce over 30 neutrons for each incident proton to allow the reactor to operate far below criticality to generate electricity or process heat while reducing high-level waste disposal costs. This commercial application has the additional attribute of addressing climate change.

INTRODUCTION

The construction, replacement, and operating costs for klystron power sources now used for superconducting RF (SRF) accelerators are high. In their most cost-effective configuration, one high-power klystron drives several SRF cavities that have separate requirements for phase and amplitude control, requiring additional phase and amplitude control devices for each cavity. Magnetron RF power sources for single cavities can cost much less and operate at much higher efficiency than klystrons, but they do not have the phase and amplitude control or lifetime needed to drive SRF cavities for NP particle accelerators.

Starting in 2021, Muons Inc. (MUONS) has been working with Richardson Electronics (RELL), a supplier of many commercial vacuum tubes, including magnetrons used for industrial applications. The RELL production-line approach to manufacturing quantities of tubes according to MUONS designs and specifications has started and has already been applied to the first prototype of the 1497 MHz, 15 kW tube (built under STTR grant DE-SC0013203) that can be the basis for a plan to replace CEBAF klystrons. The payback time for the replacement in power savings alone has been estimated to be about 5 years. In the next months, the prototype will be power tested at RELL and shipped to JLab for tests. Figure 1 shows the prototype 1497 MHz magnetron in the bakeout oven at RELL.

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Figure 1: The prototype 1497 MHz magnetron in the bakeout oven at RELL, showing the ion pump used for conditioning.

In order to properly compensate for microphonic and Lorenz detuning of SRF cavities, injection locked magnetron techniques will need to be developed. MUONS has numerical simulation models and experimental demonstrations at 2.45 GHz that have generated patents and predictions of a broader range of power control, better phase stability, higher efficiency, and longer tube lifetime with subcritical anode voltage operation. One patent, for example, describes the operation of a pulsed magnetron that does not require an expensive HV modulator.

TECHNICAL APPROACH

One purpose of this proposed project is to bring on board a manufacturing partner, Richardson Electronics, and incorporate and study various techniques that will enhance the magnetron operation for NP applications:

- Further investigate operating in sub-critical conditions with injection locking signals
- Minimize the life-cycle costs
- Novel surface coatings to eliminate outgassing from the iron polepieces
- Model injection-locking magnetron design variables which may improve injection-locking gain, for example: Qext and number of vanes.
- Filament voltage control to minimize thermal proficle due to return electrons
- Permanent magnet design to replace solenoid field while keeping the trim coil for amplitude modulation

Several areas are described below, along with design elements for optimization the life-cycle costs of refurbishing.

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Novel Magnetron Techniques for SRF Cavities - Subcritical Voltage

Muons, Inc has previously investigated the idea of changing the electric and magnetic parameters of a single magnetron fast enough to follow the frequency jumps due to vibrations of the cavity. However subcritical voltage operation has been invented that not only solves the problem of phase and power control, but has the added advantages of improved efficiency, simpler construction (no trim magnet needed), and the promise of longer tube lifetime.

Muons, Inc. supported the development of a kinetic model of magnetron generation [1], substantiating a novel method of power control in the range ≈10 dB based on a wide-range current control in a magnetron driven by a -10 dB resonant injected signal (US Patent No: 10374551). This novel method of magnetron control of SRF cavities has benefitted from developments in theory, simulations, and experimental measurements. Figure 2 shows the first demonstration of the wider range of power control in a magnetron using such an injection-locking signal range and rxesults of measurements, red line shows extrapolation with B-spline fit [2].

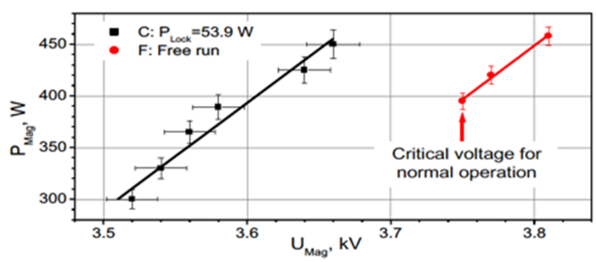

Figure 2: Power vs Cathode Voltage. With no injection locking signal, the red points showthe allowed range of power. The black points show the wider range of power of the same tube with a -10 dB locking signal.

Life Cycle Costs

The lifecycle costs for any magnetron RF system includes both extended operating times and reduced refurbishing costs. A significant market is already in play which includes reworking magnetrons by replacing the filament stalk and other components and selling the refurbished tube at one-half the cost of a new tube. Improving the processes by which this occurs with the lowest possible cost is a benefit to both the customer and manufacturer. In this project we will explore the design changes which make this process most cost effective.

Areas to study depend to a large extent to the manufacturer's established processes. For example, the use of RF brazing as opposed to furnace brazing is a quicker process but requires the additional fixturing required to maintain concentricity and uniformity of heating. RELL has the RF braze equipment, tooling, and personnel who have relied upon this technique. Their expertise will be utilized in designing assemblies and specific tooling requirements to implement these process manufacturing techniques.

Eliminate Surface Outgassing

A novel addition to magnetron production is proposed: applying a non-evaporable getter coating to the surfaces of the magnetron. In this way, the outgassing surface is converted to a pump. It is the iron polepieces and cupronickel seal rings that tend to have trapped gases in microscopic pipes due to the manufacturing of either bar or sheet stock. Typically, bar stock is used for seal rings while sheet stock is used for polepieces. Yet for some pole piece configurations the orientation of the vacuum pipes will always lead to contamination of the vacuum and neither sheet nor bar stock will eliminate "pipes" from influencing the vacuum integrity of the magnetron. This is a novel approach in magnetron construction and could have significant improvement on the life-cycle costs, shown in Figure 3.

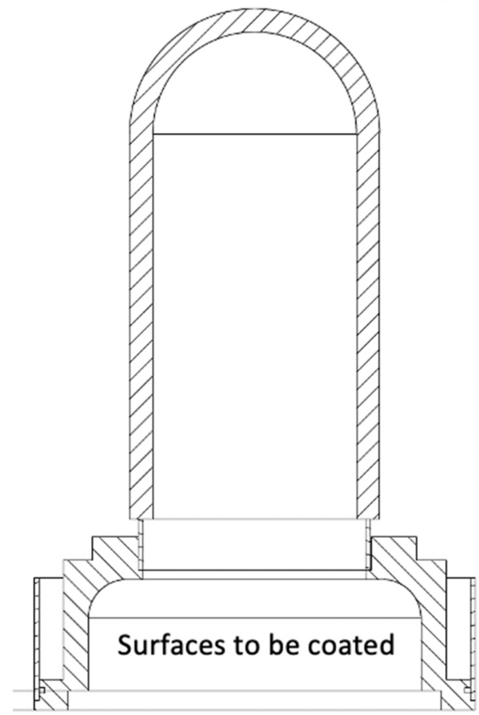

Figure 3: This is a typical output window assembly and the surfaces to be coated are indicated.

This approach to using getter coatings have been experimented with some success at various storage ring designs around the world. The trick in the case of using this technique in a magnetron is to find the right surfaces to coat. Our experiments will include the iron parts as noted above that are typically plated to copper to reduce RF losses. The region between the antenna and the output polepiece is possible location. Other locations will be experimented with.

Qext (Q_L)

Qext is classically determined to maximize the efficiency of the magnetron by limiting the amount of power that is dissipated on the anode and antenna. Qext has not been optimized for the injection locking operation of the magnetron. There have been studies that have identified a relationship between the Qext and the amount of power required to injection lock the magnetron over a given

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bandwidth. This becomes one of the factors in limiting how much gain the system can achieve.

Typically, Qext is chosen based on the balance of thermal loading of the anode structure and the antenna. The higher the Qext, the more energy is dissipated in the resonant structure; the lower, the hotter the antenna. However, in this stage of the analysis we will be determining the optimum Qext for injection locking. Since RF energy will be added to the magnetron from the injecting signal, the Qext may be optimized higher in value. This is typically not done for non-injection locked magnetrons.

Filament

The standard operational technique to extend the life of the magnetron is to lower the filament voltage to compensate for the back heating of the filament due to returning electrons and ions, to reduce the buildup of evaporants onto the anode. Typically, this is a prescribed process built into the power supply reducing the filament voltage by specific voltage levels. The most efficient system would include an active feedback system which tests the operation of the magnetron power level as a function of filament voltage. Continual verification of the lowest possible filament voltage given the operating demands on the magnetron would provide for the longest life.

In addition, the resistivity of the filament is a measure of the temperature. It can be used in the feedback loop to maintain a constant temperature. The technique is straight forward, however the time constant of such a feedback loop is rather large due to the thermal mass of the filament. In this project a feedback system will be designed and tested for optimizing the filament for extended life operation.

Magnetic Field

The magnetic field requirements for a magnetron are well established and experimentally determined using an electro-magnet. For the TJNAF application, a permanent magnet design will both improve efficiency and reduce costs. In this project, a permanent magnet design will be incorporated that has been optimized for the amplitude modulation of the magnetron. This means the electro-magnet used for amplitude modulating the magnetron will be in parallel with the permanent magnet which provides the biasing. This allows for a unique operating condition that may include a slight adjustment of the biasing field while modulating the current which drives the amplitude modulation. This would imply the use a voltage waveform for the AMing electro-magnet with an adjustable DC component. The material of the permanent magnet will also be chosen with regard to the thermal stability of the material. Samarium cobalt is a common choice in the microwave tube industry as shown in Figure 4.

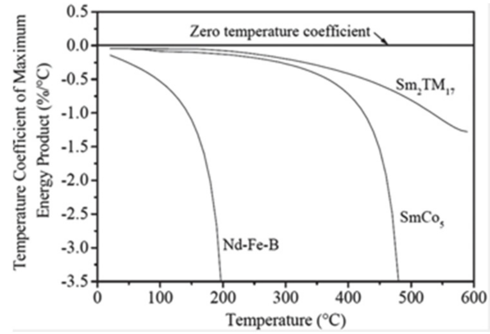

Figure 4: SmCo5 has a much lower temperature coefficient than Nd.

TECHNICAL GOALS

A magnetron suitable for 1497 MHz klystron replacements at Jefferson Lab will be constructed at RELL and power tested with our novel patented subcritical voltage operation methods in preparation to drive an SRF cavity. The critical areas of magnetron manufacturing and design affecting life-cycle costs that will be modeled for improvement include: Qext, filaments, magnetic field, vane design, and novel control of outgassing.

TECHNICAL BENEFITS

The most immediate benefit of this project is to make SRF accelerator projects more affordable for NP and other users of SRF Linacs. In terms of capital cost, for example, a cost projection by ANL for a 1 GeV 20 MW proton accelerator that cost $800M using IOTs for rf power was reduced by $180M using magnetrons in place of the IOTs. The reduction in operating cost as described above for the CEBAF machine by using magnetrons instead of klystrons had a payback time of 5 years due to electricity cost savings.

One of the most attractive commercial applications for SRF accelerators is to drive subcritical nuclear reactors to burn Light Water Reactor Spent Nuclear Fuel (LWR SNF). A 1 GeV proton beam hitting an internal uranium spallation neutron target can produce over 30 neutrons for each incident proton to allow the reactor to operate far below criticality to generate electricity or process heat while reducing high-level waste disposal costs. This commercial application has the additional attribute of addressing climate change.

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