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SIMULATION STUDY USING AN INJECTION PHASE-LOCKED MAGNETRON AS AN ALTERNATIVE SOURCE FOR SRF ACCELERATORS

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Abstract

As a drop-in replacement for the CEBAF CW klystron system, a 1497 MHz, CW type high efficiency magnetron using injection phase lock and amplitude variation is attractive. Amplitude control using magnetic field trimming and anode voltage modulation has been studied using analytical models and MATLAB/Simulink simulations. Since the 1497 MHz magnetron has not been built yet, previously measured characteristics of a 2.45GHz cooker magnetron are used as reference. The results of linear responses to the amplitude and phase control of a superconducting RF (SRF) cavity, and the expected overall benefit for the current CEBAF and future MEIC RF systems are presented in this paper.

MAGNETRONS VERSUS KLYSTRONS

Magnetrons used in industrial and medical accelerators normally have 85-95% electronic efficiency, much higher than typical klystrons within the same perveances [1]. As a comparison shown in Fig. 1, this advantage is independent of the wavelengths (which are given in Fig. 1 in cm marked up next to their data points). The pictures show the two types of klystrons used at CEBAF, one 2.45GHz cooker magnetron (used in our experiment in ref. [2]) and one family of L3 magnetrons (potential candidate for MEIC SRF system) for the reference data points. The fundamental difference between the two types of devices is the electron bunch formation: linear motion in the klystron; circular motion in the magnetron. Space charge effects in the motion dominate the efficiency. The spoke-on-hub bunches in a magnetron interact with the anode RF cavity in multi-gaps over multiple-passes. Space charge de-bunching effect on the spokes is reduced. The beam bunching and power extraction in a klystron is a linear interaction with cavity gaps and only one pass. Also the spent energy from decelerated electrons in a magnetron is returned to the cathode which further helps the emission. But in a klystron, it is dumped into a collector which reduces efficiency further.

The traditional klystron works as a high gain linear amplifier driven by a low level signal. Its output phase and amplitude can be controlled at both low and high levels. It can be also operated in either CW or pulsed mode with a modulator. The capital cost is in the range \$5-25/output Watt depending on the power and production quantity. The magnetron is a saturated oscillator which does not need a drive for oscillation at high power output, but can be seeded by a back injection signal through its output waveguide, in which case its output phase will follow the injection phase. It can be also both operated in CW or pulsed modes as long as the pulse width is longer than the magnetron starting time. If it is designed properly, it can be operated in both high gain and high efficiency as well as low production cost, e.g. less than \$1/output Watt for a typical oven magnetron.

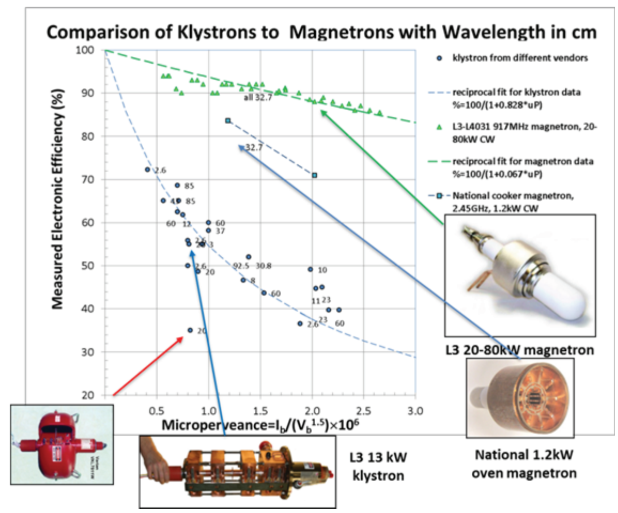

Figure 1: Comparison of electronic efficiencies between klystrons and magnetrons

BENEFITS TO CEBAF AND MEIC

The ultimate goal of using magnetrons instead of klystrons for the current CEBAF and future MEIC machines is the both capital and operation cost reduction in the electric power. Using the numbers from the RF power requirement for the current designed MEIC complex [3], a total DC power saving of 7.2-9.7MW has been estimated. This results \$3.9-5.2M annual power cost saving if 41 weeks operation is assumed. Savings for CEBAF operation and other MEIC systems are shown in Table 1.

First demonstration and performance of an injection locked CW magnetron to phase control a SRF cavity was done at JLab in conjunction with Lancaster University, UK, in 2010 [1] with accuracy of 0.95° rms, -23.5dB injection input and 540W output.

However, using magnetrons to drive MEIC or other SRF accelerators like CEBAF still needs more R&D work particularly to demonstrate the amplitude control of a magnetron while preserving the high efficiency. If the magnetron can be operated as a voltage controlled oscillator while maintaining the injection phase lock, then this cost benefit will be significant to the accelerator community.

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Table 1: RF Power Savings Estimate for CEBAF and MEIC

	CEBAF 12GeV	E-Ring PEP-II 10GeV	Ion-linac Pb 60MeV/u	Booster	Ion-Ring Pb 40GeV/u	CC-ERL Cooler 55MeV	Crab (16+6)×2MV	
Frequency (MHz)	1497	476.3	162.5/325	0.6-1.3	1.2-1.3	952.6	476.3/952.6	952.6
Duty Cycle (%)	cw	cw	0.5	ramp	ramp	cw	cw	cw
Cavity	sc 2K	nc	nc	nc	nc	sc 2K	nc/sc 2K	sc 2K
Max Peak Power (MW)	2.76	12.79	42		0.36	0.73	0.12	0.0023
Ave. Power (MW)	2.76	12.79	0.46	0.084	0.36	0.73	0.12	0.0023
Klystron DC-RF Efficiency (%)	35-51	67	50-60	na	na	50-60	50-60	50-60
Magnetron DC-RF Efficiency (%)	80-90	80-90	80-90	na	na	80-90	80-90	80-90
DC Power Saved (MW)	3.4-3.8	3.1-4.9	0.26-0.35	na	na	0.41-0.55	0.07-0.09	0.0013-0.0017

MAGNETRON EFFICIENCY ISSUE WITH OTHER AMPLITUDE CONTROLS

As an alternative to using magnetic field trimming and anode voltage variation, it is possible to use the injection phase lock plus phase modulation (PM) [4] or frequency modulation (FM) and vector sum (VS) schemes [5] for the magnetron amplitude control. Using the SRF cavity itself as a narrow passband filter, the RF power thus produced in the sidebands will be reflected to the power circulator load. This PM scheme with one magnetron has no fundamental difference to the VS scheme using two sources. The magnetron system efficiency drops as the amplitude is lower than the saturated power since reflected power goes to the circulator load than cavity field and is wasted. The same thing happens for the VS scheme when using a hybrid power combiner. Figure 2 shows the efficiency calculation for these two schemes.

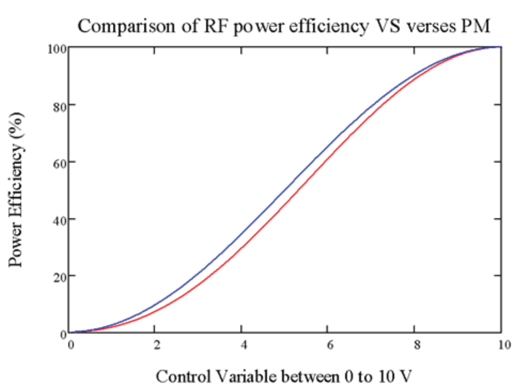

Figure 2: magnetron system efficiency using PM (red) or VS (blue) scheme, control variable from 0 to 10 V represents the power amplitude from 0 to 100%.

Due to the microphonic vibration of a SRF cavity, the cavity with or without beam loading mostly works at <40% of saturated klystron power level, so the efficiency of such magnetron system will be less than 30%.

CONTROL SYSTEM STUDY USING ANALYTICAL MODELS AND SIMULINK

A Mathcad program was first developed based on the Vaughan analytical model [6]. A 1.5GHz magnetron in 2D shape was then designed as in Fig. 3. The Va-B staring and working points of this magnetron are shown in Fig. 4.

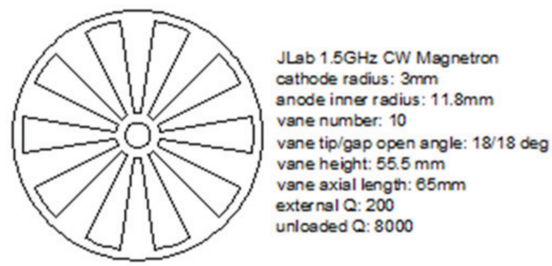

Figure 3: 1.5GHz magnetron design by Vaughan model.

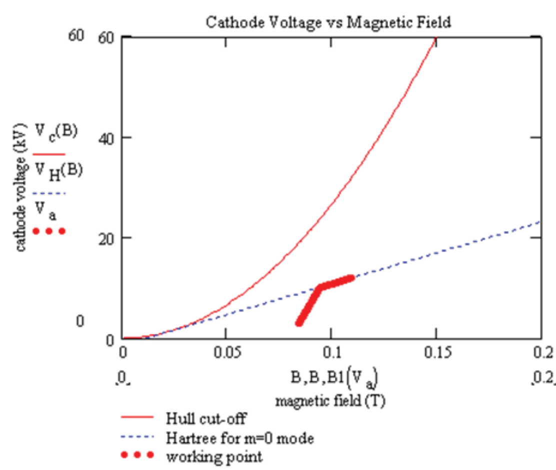

Figure 4: 1.5GHz magnetron starting and working points.

To control the magnetron amplitude from 2kW to 18kW, the magnetic field and anode voltage needed to be changed simultaneously as in Fig. 5. The characterization curves of anode Va-I, output power P (tube electronic efficiency η) and frequency push dependence to the anode current are then implemented in the Simulink simulations.

The Simulink simulation is intended to model the steady-state performance of the system without using a particle-in-cell (PIC) simulation for the magnetron. To understand the CEBAF control requirement and new LLRF hardware design specification, control diagrams for the SRF cavity and CEBAF beam loading had been developed. The portion normally containing a klystron model used as a linear amplifier has been extensively modified to substitute the magnetron model. Figure 6 shows this simulation diagram.

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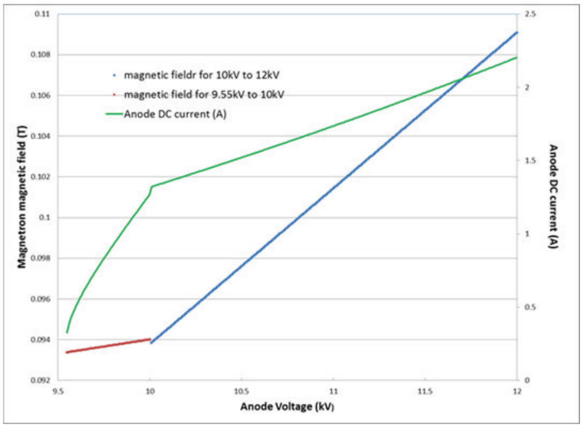

Figure 5: Magnetron magnetic field and anode voltage variations for the magnetron amplitude control.

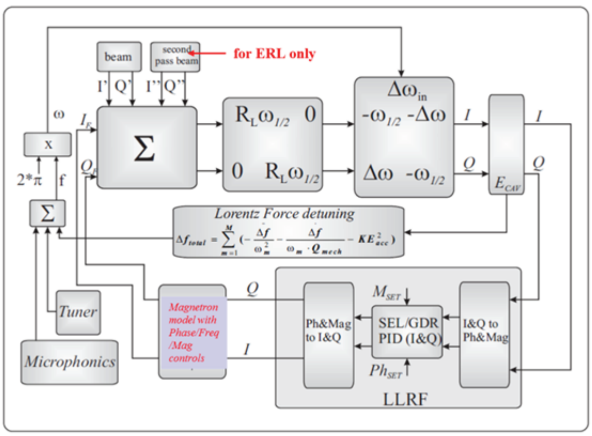

Figure 6: Simulink block diagram of magnetron driven RF system to control the SRF cavity with beam loading, Lorentz Force Detuning (LFD) and microphonics.

Injection phase lock to a magnetron can have a time response to a fast transient of 90° from injection to magnetron output of the order of 0.5μs [5]. So it is fast enough to handle any transient state like turn by turn beam loading, microphonics and the LFD. Demonstrated injection phase lock error of 1° rms if applied to JLab's C100 cavities corresponds to 0.4 Hz rms frequency of microphonic variation.

To achieve high performance in a SRF cavity with beam loading, the magnetron's Low Level RF (LLRF) control has been designed in two lock loops. In the frequency lock loop, the characteristic anode Va-I curve, output power (the tube electronic efficiency), frequency dependence to the anode current (pushing by Vaughan model) and the Rieke diagram (frequency pulling by the reactive load) are included. In the phase lock loop, the Adler equation [7] governing the magnetron output phase following the injection phase within the locking power is used. In a recent study we have found that Chen's model [8] has advanced to Adler's for the phase lock stability and locking bandwidth.

Current LLRF SEL/GDR control system with klystron was simulated first with PI regulator (P=80 I=20) which can satisfy the C50 cryomodule operational amplitude and phase error requirements of 0.01% and 0.5 deg for microphonics background of ~ 3 Hz rms (using 6σ techiques)

Using a -30dB injection signal, injection phase lock itself can control within +-0.8MHz frequency pulling by the anode current, otherwise a frequency pushing by the output admittance needs to be used. For a large amplitude variation, magnetron control can use a linear response of the anode voltage and magnetic field, so the power output can be linearly changed by the anode voltage. The maximum modulation rate depends on the magnetic field trimming coil's inductance. For the need of microphonic control, it is sufficiently fast. To get both amplitude and phase control, different gain is needed in each regulation slope rate. This different gain set can be programmable in the modern digital control.

CONCLUSIONS

The magnetron can be modelled as an anode voltage controlled oscillator, the loop gain and bandwidth of the LLRF control determine the locking stability and accuracy. Table 2 lists the preliminary simulation performance data.

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

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. This will be performed for a commercial magnetron in the near future. Frequency pulling by the output circuit of magnetron has not been simulated in the current model so far.

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