PHASE LOCKED MAGNETRONS FOR ACCELERATORS

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Abstract

Magnetrons offer lower capital costs and higher efficiencies than klystrons, however are natural oscillators rather than amplifiers. This paper reviews techniques and issues for applying high efficiency L band magnetrons to long pulse, high intensity proton linacs. Reference is made to a proof of principle experiment whereby the phase of an SRF cavity was accurately controlled when energised by a magnetron.

INTRODUCTION

Early split ring anode magnetrons as described by Elder in 1926 [1] were operated both as amplifiers and oscillators. A magnetron is characterized by a d.c. electric field applied between a cylindrical cathode and a surrounding anode with a d.c. magnetic field that is transverse to the electric field. The development of high current cathodes in the years just prior to 1939 [2] allowed the first high power magnetron to be developed in 1940 [3]. The resonant circuits that were previously outside the vacuum envelope became solid copper anode blocks to dissipate heat from the impacting electrons.

By 1943 the electronic behaviour of the cavity magnetron and its equivalent circuit were well understood. Reike's contribution in Collin's book [4] identifies the fundamental electrical quantities for the magnetron as the d.c. magnetic field B, the RF output power P_{out}, the frequency f, the load impedance Z_L, the d.c. current I_{dc} and the d.c. voltage V_{dc} applied between the anode and the cathode.

Frequency Pulling

The pulling characteristic of a magnetron is a map of how its frequency is perturbed by a load. It can be understood by representing the magnetron as a negative resistance oscillator as depicted in Fig. 1.
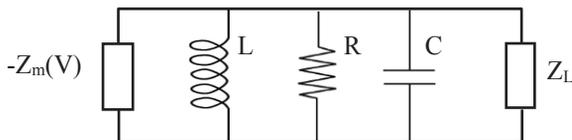

Figure 1: Equivalent circuit for a magnetron.

In Fig. 1 the values of L and C are chosen to give the operating mode frequency of the magnetron and the impedance that the anode resonator presents to the electronic current. The value of R is chosen to give the correct Ohmic heating in the RF circuit. The negative impedance $-Z_m$ represents the mechanism by which the electrons generate RF in the resonant anode structure. The

value of Z_m depends primarily on the RF field in the anode structure, the d.c. current I_{dc} and the magnetic field B. Define the RF voltage V as the instantaneous RF voltage between anode vane tips. The magnitude of the steady state RF voltage is then achieved after I_{dc} has adjusted itself to make

$$\text{Real}\{-Z_m(V, I_{dc}, B) + Z_L\} + R = 0 \qquad (1)$$

The circuit of Fig. 1 dictates the general form of the Magnetron Rieke diagram as illustrated in Fig. 2. The figure shows that reflecting power back to the magnetron with a $\pm 90^o$ phase shift increases or decreases the magnetron frequency respectively. It should be noted that reflecting power in phase or 180° out of phase will change the power output. The outer circle in Fig. 2 represents a reflection coefficient of 0.8. Reflecting 10% of the power back to the magnetron changes the output by 8% and this can be plus or minus depending on the phase of the reflection. The skewing of the constant frequency lines in this figure are probably as a consequence of the anode being cooler and hence smaller at lower power levels.
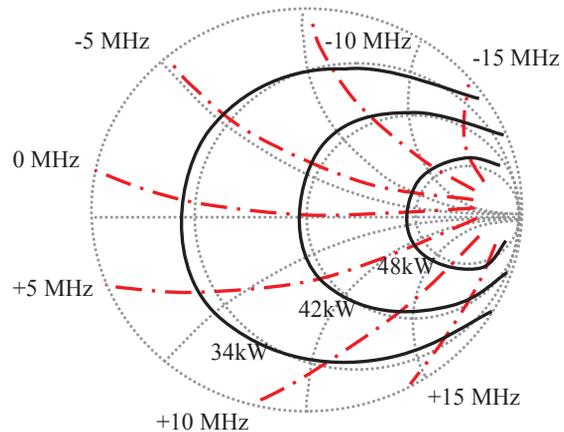

Figure 2: Rieke Diagram re-drawn from Collins [4] for a type 725A Pulsed X band magnetron, B = 0.55T, Peak anode current = 10A.

Injection Locking

The magnetron pulling characteristic enables phase locking with an injected signal. If the magnetron's phase falls behind or moves in front of the injection signal's phase then the magnetron sees a complex impedance that moderates its frequency. This moderation acts to move the magnetron's phase back to the injection signal's phase. Prior to the development of circulators the phase of two magnetrons could be locked to a third magnetron using 3dB hybrid splitters [5]. Varian repeated this experiment by phase locking two high power X band magnetrons to a TWT with 13dB of gain for ~ 9µs pulses.

They achieved frequency stability at the 0.4 degree level and presented the work at PAC in 1991 [6].

Injection locking is used to force the phase of an oscillator to follow the phase of a driver hence we also refer to injection locking as phase locking. Phase locking a magnetron is most useful for accelerator applications when the injection signal has a much smaller power output than the magnetron. When a circulator is used to introduce the injection signal to the magnetron thereby isolating the source from the output, the RF system is called a reflection amplifier [7, 8]. An equivalent circuit for a magnetron operated as a reflection amplifier is shown in Fig. 3.
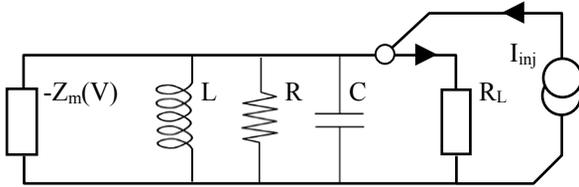

Figure 3: Equivalent circuit with injection locking.

As the circulator prevents reflection from the load then the load becomes purely resistive with a value equal to the waveguide impedance. The magnetron output voltage is now determined as

$$-\frac{V}{Z_m(V)} + \frac{V}{j\omega L} + \frac{V}{R} + j\omega C V = -\frac{V}{R_L} + I_{inj}$$

Assuming that the injection signal is matched to the waveguide so that $I_{inj}R_L = V_{inj}$ and setting $\omega_o = 1/\sqrt{LC}$ and $Q_L = \omega_o R_L C$ this equation becomes

$$\left(\omega_o^2 - \omega^2\right)V + j\frac{\omega_o\omega}{Q_L}\left(1 + \frac{R_L}{R} - \frac{R_L}{Z_m}\right)V = -j\frac{\omega_o\omega}{Q_L}V_{inj}$$

The transient behaviour associated with this circuit equation is determined by the non-linear differential equation.

$$\ddot{V} + j\frac{\omega_o}{Q_L}\left(1 + \frac{R_L}{R} - \frac{R_L}{Z_m}\right)\dot{V} + \omega_o^2 V = -\frac{\omega_o\omega}{Q_L}V_{inj}\sin(\omega t) \tag{2}$$

If the coefficient of $\dot{V}$ were to be zero for all voltages V then locking would be possible for any injection frequency. When Z_m is a function of V this equation exhibits a finite locking range.

Locking Range and Bandwidth

Adler's approximate treatment for this type of oscillator [9] has acceptable validity for magnetrons. His treatment shows that the phase shift across a negative resistance oscillator when it is locked is given by

$$\sin\psi = Q_L \frac{V}{V_{inj}} \frac{\omega_o^2 - \omega^2}{\omega_o\omega} \approx 2Q_L\sqrt{\frac{P_{out}}{P_{inj}}}\frac{f_o - f}{f_o} \tag{3}$$

where f is the injection frequency and f_o is the natural frequency of the magnetron. Injection locking is only possible when the RHS is less than 1. This condition only occurs when the natural frequency of the magnetron is very close to the injection signal frequency. In the frequency range where locking is possible the frequency of the magnetron follows the frequency of the injection signal. From the Rieke diagram it can be seen that the output power must also vary with the input power however this variation is very small when the amplitude of the injection signal is small.

Adler's differential equation for the phase predicts a time constant for locking to occur. The reciprocal of this time constant gives the effective bandwidth of the injection locked magnetron Δf as

$$\Delta f = \frac{f_o}{2Q_L}\sqrt{\frac{P_{inj}}{P_{out}}} \tag{4}$$

APPLICATION TO ACCELERATORS

Injection locked magnetrons can only be considered for accelerator applications when they have sufficient bandwidth, sufficient power and sufficient power regulation. Magnetrons become of interest where cost reduction for the RF system and its operation is important. Table 1 makes a subjective comparison of klystrons and magnetrons.

Table 1: Tube Comparison

	Magnetron	**Klystron**
Peak Power	Lower	High
Average power	Lower	High
Gain	Lower	High
Tuneable range	Larger	Small
Instantaneous bandwidth	Smaller	Small
Slew rate	Smaller	Small
Noise figure	Higher	Lower
Best Efficiency L band	~ 90%	ILC ~ 69%
Best Efficiency X band	~ 50%	XL5 = 40%
Pushing figure	Significant	Significant
Pulling figure	Significant	
Amplifier cost	Low	High
Modulator & magnet cost	Lower	High
Size	Small	Large

Unless size and weight are issues one would not use a magnetron if one can afford a klystron. Klystrons are most cost effective when used at the highest power levels that standard designs permit.

Table 1 suggests that magnetrons are best suited to L band applications where they can be 90% efficient and for situations where the power requirement is far below the level where klystrons are most cost effective. An application area meeting this criterion is high intensity superconducting proton linacs. For acceleration up to several GeV while the protons are not fully relativistic it is preferable to drive each cavity separately. Taking CERN's nominal SPL design as an example [10], then power requirements for individual superconducting elliptical cavities lie in the range ~200kW to 900kW. The output power of long pulse and continuous wave magnetrons is often constrained by cathode over-heating. Industrial processing magnetrons readily achieve c.w. output powers of 100 kW, at 915 MHz with an efficiency of 90% which suggests that for a long pulse proton linac with a duty cycle < 10% then operation at the 1 MW level is easily achievable. For reasons of flexibility, cost and efficiency, magnetrons are currently being evaluated as an option for Fermilab's proton linac [11].

Bandwidth and Phase Control

An RF system parameter that determines the ultimate phase control achievable in a superconducting cavity is the amplifier bandwidth. Table 2 applies (4) to determine bandwidth for three nominal cases, a 1MW magnetron driven by a low cost television IOT, a 1 MW magnetron driven by a 5 kW solid state amplifier and a domestic cooker magnetron driven by a 1 W amplifier.

Table 2: Magnetron Bandwidth

Freq. (MHz)	Output (kW)	Injection (kW)	Amp. (dB)	Q factor	Bandwidth (MHz)
704	1000	50	13	50	1.57
704	1000	5	23	50	0.5
2450	1	0.001	30	100	0.39

The case of the cooker magnetron in row 3 is representative of the demonstration of phase control by Dexter et al. [12] for a superconducting cavity with realistic microphonics and an external Q factor appropriate to accelerator applications [12]. (*Please note that table 2 refers to the magnetron Q factor not the accelerator cavity Q factor*). In this work 8dB of suppression was achieved for a 50Hz microphonic and 21dB of suppression was achieved for 60 Hz power supply ripple. The r.m.s. jitter for this experiment is reproduced in Fig. 4 and has a value of about 1 degree. During this experiment the frequency stabilization circuit described in [13] was de-activated due to technical difficulties hence the LLRF gain for cavity control had to be reduced and as a compensation the injection power increased from -30dB to about -23dB. Had the frequency stabilisation been working as intended then an even better result would have been achieved. Phase control at the level of 1 degree is just sufficient for SPL as this is the magnitude of errors assumed in successful design simulations [10].
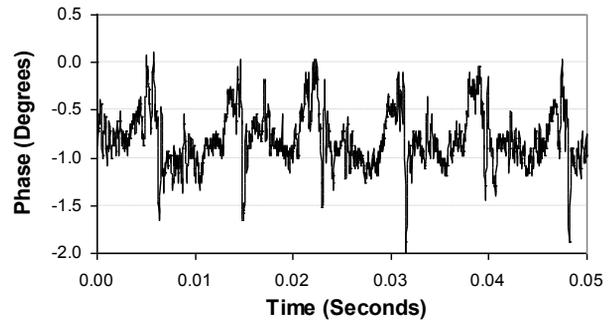

Figure 4: Phase of a superconducting cavity powered by a magnetron in a test stand at JLab.

How much power one chooses to use for the drive amplifier depends very much on the cost and availability of drive amplifiers. For the case of the IOT driver in row 1 of table 2, the gain is a modest 13dB but the bandwidth is much improved compared to row three where tests have been undertaken. A gain of 13dB is sufficient to keep almost all the efficiency gain of using a magnetron, i.e. 95% of the power is generated at 90% efficiency and 5% of the power is generated with >50% efficiency hence the overall efficiency is >88%. A huge cost saving associated with this scheme is that both magnetron and the drive IOT can fit and operate reliably in the accelerator tunnel adjacent to cavity, (subject to screening magnetic fields).

Equation (5) describes the situation when a controller with gain c_p acts with time delay T_{delay} to correct an in phase or quadrature component A of the RF voltage in a cavity to bring it closer to a set point V_{sp}

$$\frac{Q_e}{\omega_o}\dot{A} + \frac{Q_e}{2Q_L}A = -c_p\left\{A\left(t - T_{delay}\right) - V_{sp}\right\} \qquad (5)$$

where Q_e and Q_L are external and loaded Q factors for the cavity respectively. In this instance the maximum gain for stable control is determined by the inequality

$$c_p < \frac{\pi Q_e}{2\omega_o T_{delay}} \sim \frac{\text{amplifier bandwidth}}{4 \times \text{cavity bandwidth}} \qquad (6)$$

The derivation of this result together with a more complicated result for PI controllers is given by Dexter and Burt [14]. Most of the delay would come from any narrow band amplifier in the feedback loop.

The level of phase control in the cavity for unpredictable disturbances is proportional to the controller gain which is limited primarily by amplifier bandwidth. With respect to table 2 the bandwidth between row 3 and row 1 is increased by a factor of 4 hence one might expect phase errors to be reduced by a similar factor. It should also be noted that as CERN's SPL has relatively high beam loading, the cavity bandwidth is higher than that used for the demonstration [12].

For any accelerator RF system one would want the drive amplifier to have a wide bandwidth albeit at a lower efficiency, so that the overall bandwidth of the RF amplifier chain is not reduced. Standard television IOTs

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have bandwidths exceeding 8 MHz. As cavity phase and amplitude errors increase with control system time delay, there is a benefit in having the power amplifiers and control circuits close to the cavities. The layout one might adopt for driving a magnetron with a television IOT is given in Fig. 5.
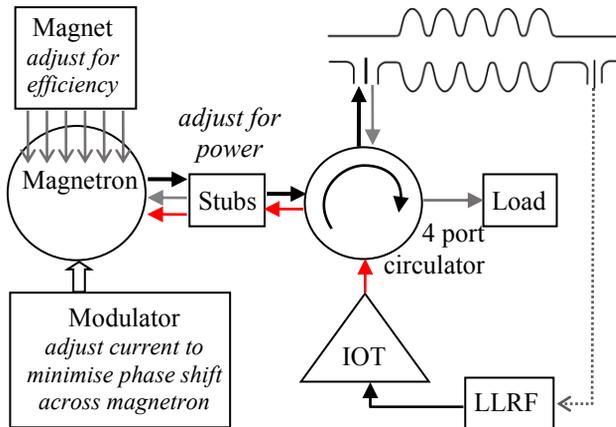

Figure 5: RF Layout for magnetron driven by an IOT.

Whilst other configurations are possible such as combining the output from two magnetrons with a phase separation to allow fast full scale amplitude modulation [12] the configuration given here is expected to have 4% fast amplitude modulation and 50% amplitude modulation pulse to pulse (4% assumes a 50kW IOT, a 1 MW magnetron and a pulling characteristic similar to Fig. 2). Even more amplitude variation is available on a time scale over which the magnetic field can be varied.

Stabilisation and Amplitude Control

For a magnetron it is useful to think of B, V_{dc} and Z_L as inputs and I_{dc} , P_{out} and f as outputs. There is one more important parameter that was not given in Reike's list and that is cathode temperature T_c . One has limited control of T_c by varying heater power as the cathode self heats by back bombardment. The three outputs have a significant dependency on each of the four inputs. In particular if one changes the load impedance or the injection level both the frequency and the power output change. The Reike diagram tells one how to change amplitude and phase of the injection RF so as to maintain constant power output.

As the injection power is limited then with injection alone, only small changes can be made to the power output. These small changes however can be made on a time scale much less than the bunch train length and could be used to compensate small changes in bunch charge and hence beam loading during a train. Much larger changes can be made in the power output by reflecting power back to the magnetron by waveguide tuning elements labelled as stubs in Fig. 5. Power variation by this method depends on how far the tuning element can be moved before arcing occurs. In the absence of injection locking, the tuning elements can be moved to maintain frequency.

When a magnetron is injection locked there will be a phase variation through the magnetron that depends on how far the frequency of the free running magnetron under the same input conditions would be from the injection signal. An estimate of the phase shift is given by Adler's solution (3). If the dependency of the negative impedance Z_m on the RF voltage is known then a better value is found by numerical solution of the non-linear differential equation (2). In order to maximise the magnetron's bandwidth as an amplifier then the natural frequency of the magnetron needs to be brought as close to the drive frequency as possible. As the magnetron's natural frequency depends on its operating point and the anode temperature then active control is required.

A fast way to do this is to exploit the magnetron's pushing characteristic [13] whereby changing the d.c. anode current changes the natural frequency of the free running magnetron. For the injection locked magnetron changing the anode current changes the phase shift between the injection signal and the RF output. This anode current adjustment would be made pulse to pulse by the modulator. With a suitable look up table the waveguide tuner could be adjusted at the same time to maintain power or to change power to a new level.

Heater Power

The magnetron cathode is both a source of thermal electrons and secondary electrons emitted as a consequence of back bombardment. Electrons are accelerated out from the cathode by the d.c. electric field and then trace a curved arc that would terminate back at the cathode under the influence of the d.c. magnetic field. In the presence of an RF field some electrons get accelerated and some get retarded. Those which get retarded can no longer get back to the cathode on the initial arc. Most of these electrons continue to the anode. If the RF field is large then electrons that return to the cathode have sufficient energy to cause secondary electron emission. As a consequence of these processes there is considerable space charge around the cathode causing the d.c. electric field to be reduced at the cathode. If the field at the cathode becomes very small then the magnetron becomes noisy and phase locking becomes difficult. As the electric field falls to zero, the current to the anode becomes space-charge limited. When the anode current is not space charge limited then it is either thermally limited or back bombardment limited. Experiments on the phase modulation performance of magnetrons show that bandwidth increases with heater power almost up point that lock is lost [16].

Efficiency

The highest magnetron efficiencies usually occur when emission is space-charge limited. A key question is whether good efficiency can be obtained when the anode current is not space charge limited at the cathode. There is an optimum level of space charge around the cathode giving a reduced electric at the cathode, so that bandwidth is good, noise is low and locking is easy.

For the Panasonic 2M137 magnetron used for injection locking experiments [13] when operated at a power level near to 700W, the electronic efficiency fell by 7% between full heater power giving space charge limited emission and zero heater power giving back bombardment and temperature limited emission. Neither radar nor industrial magnetrons that are currently manufactured commercially have been optimised for high efficiency operation with injection locking. New developments are hence required.

MAGNETRON MODELLING

Requirements for an L band magnetron to power proton linacs has been set out above. Prior to a first prototype one would want modelling to predict

- the Reike diagram,
- the VI characteristic,
- the pushing curve,
- cathode temperature,
- variation during a pulse,
- efficiency to within 2%,
- loaded Q factor at nominal power,
- electric field at the cathode.

Our efforts to model magnetrons using finite difference time domain PIC codes have been largely unsuccessful with respect to the determining quantities and characteristics in the bulleted list above. In order to predict back bombardment and hence an accurate VI characteristic, the mesh needs to resolve electric fields to a few volts for electrons returning to the cathode. For stability when calculating the RF field a fine mesh forces small time iterations making run times impractical.

Electromagnetic field solvers are used to develop the mode structure for the anode so that the pi mode is preferentially excited. Once the magnetron has stabilised, the form of the RF field is completely dominated by the pi mode hence there is no need to undertake time stepped RF calculations. Experimentally the magnitude of the RF field is determined primarily by the external Q factor. The magnetron can be modelled by tracking electrons. The procedure is to assume an anode to cathode voltage, a d.c. magnetic field, a voltage for the RF field and a cathode temperature. The d.c electric field depends on space charge and hence on electron trajectories and the overall current. We determine it self consistently. Currents to the anode and returning to the cathode together with secondary emission are all determined directly. RF generation is determined by energy balance for each electron. The total RF output allows the Q factor at the operating point to be determined i.e. this operating point could be found for a real magnetron by adjusting the external match. Pushing is determined by the phase shift between the magnetron's spokes and internal RF voltage.

CONCLUSION

There does not seem to be any significant barrier to driving long pulse superconducting linacs with high efficiency L band magnetrons. The RF controls will be more complex than those required using klystrons. A new self consistent particle tracking model to predict magnetron performance and characteristics has been developed.

REFERENCES

[1] F.R. Elder "*The Magnetron Amplifier and Power Oscillator*", Proc I.R.E. pp 159, No 2, April 1925.

[2] Y. Blanchard "*Maurice Ponte and Henri Gutton"* CAVMAG 2010, Bournemouth, IEEE conference publication, DOI: 10.1109/CAVMAG.2010.5565573.

[3] H.A.H. Boot & J.T. Randall "*The cavity Magnetron*", Part IIIA: Radiolocation, J. Inst. Elec. Eng, Jan 1946, pp928-938, DOI: 10.1049/ji-3a-1.1946.0183.

[4] G.B. Collins, "*Microwave Magnetrons*", MIT Radiation Laboratory Series, McGraw-Hill 1948.

[5] J.C. Slater "*The Phasing of Magnetrons*" MIT Technical Report 35, 1947.

[6] T.A. Treado et al. "*Power-combining and injection locking magnetrons for accelerator applications*", Proc IEEE Particle Accelerator Conf., San Francisco, CA 1991, pp. 702-704.

[7] J. Kline "*The magnetron as a negative-resistance amplifier*", IRE Transactions on Electron Devices, vol. ED-8, pp. 437 – 442, Nov 1961.

[8] H.L. Thal and R.G. Lock, "*Locking of magnetrons by an injected r.f. signal*", IEEE Trans. MTT, vol. 13, No 6, pp. 837-846, 1965.

[9] R. Adler "*A study of locking phenomena in oscillators*" Proc IRE, vol 34, June 1946.

[10] F. Gerigk et al "*Conceptual Design of SPL II*" CERN-2006-006.

[11] G. Kazakevich et al. "*A two stage injection-locked magnetron for accelerators with superconducting cavities*", IPAC 2012, WEPPC059.

[12] A.C. Dexter et al. "*First demonstration and performance of an injection locked CW magnetron to phase control a superconducting cavity*", Phys .Rev. STAB 14.032001, 2011.

[13] I. Tahir, A.C. Dexter and R.G. Carter R. "*Noise performance of frequency and phase locked CW magnetrons Operated as Current Controlled Oscillators*", IEEE Trans. Electron Devices, vol. 52, No.9, pp. 2096-2103, 2005.

[14] A.C. Dexter & G. Burt "*Phase and Amplitude Control of Dipole Crabbing Modes in Multi-Cell Cavities*", EUROTeV-Report-2008-064 November 2008.

[15] W.C. Brown, "*The high signal to noise ratio of the microwave oven magnetron and evidence of a negative feedback loop to control it*", Proc 1st Int. Workshop on Cross-Field Devices, The University of Michigan, Aug 1995, pp. 178.

[16] I. Tahir, A.C. Dexter and R.G. Carter, "*Frequency and Phase Modulation Performance on an Injection-Locked CW Magnetron*", IEEE Trans. Elec. Dev, vol. 53, no 7, pp. 1721-1729, 2006.