Magnetrons for accelerators

Amos Dexter

PLAN

• History
• Opportunities
• Current status
• Magnetron efficiency
• Magnetron phase locking

Enhanced European Coordination for Accelerator Research & Development
The Reflection Amplifier

- Linacs require accurate phase control
- Phase control requires an amplifier
- Magnetrons can be operated as reflection amplifiers

Compared to Klystrons, in general Magnetrons
- are smaller
- more efficient
- can use permanent magnets
- utilise lower d.c. voltage but higher current
- are easier to manufacture

Consequently they are much cheaper to purchase and operate

J. Kline “The magnetron as a negative-resistance amplifier,”

H.L. Thal and R.G. Lock, “Locking of magnetrons by an injected r.f. signal”,

EnEfficient RF Sources Workshop Daresbury June 2014
History

Single magnetrons 2.856 GHz, 5 MW, 3µs pulse, 200 Hz repetition are used to power linacs for medical and security applications.

Multiple magnetrons have been considered for high energy normal conducting linacs but the injection power needed for an unstabilised magnetron made it uncompetitive with a Klystron.


Overett, T.; Bowles, E.; Remsen, D. B.; Smith, R. E., III; Thomas, G. E.  “Phase Locked Magnetrons as Accelerator RF Sources” PAC 1987


Treado, Todd A.; Brown, Paul D., Aiguier, Darrell “New experimental results at long pulse and high repetition rate, from Varian’s phase-locked magnetron array program” Proceedings Intense Microwave Pulses, SPIE vol. 1872, July 1993

Courtesy of e2v
The Magnetron  A Low Noise, Long Life Amplifier

This author, a leading proponent of the transmission of power via microwave beams, describes how the common microwave oven magnetron can be externally locked to provide 30 dB of gain - resulting in a 500 watt, 70% efficient, $15, coherent microwave source.

William C. Brown
Consultant
Weston, Massachusetts

The 2450 MHz magnetron which supplies 700 watts of average power to the ubiquitous microwave oven is made in a quantity of 15,000,000 units annually at a very low price, less than $15. It has a high conversion efficiency of 70% and small size and mass. What is not generally recognized is that it has very low noise and long life properties, and that it can be combined with external circuitry to convert it into a phase-locked amplifier with 30 dB gain, without compromising its noise or life properties.
Such amplifiers are ideal for combining with slotted waveguide radiators to form radiating modules in a low-cost, electronically steerable phased array for beamed power, which motivated this study. However, there are conceivably numerous other practical purposes for which these properties can be utilized.
The low noise and long life properties are associated with a feedback mechanism internal to the magnetron that holds the emission capabilities of the cathode to those levels consistent with both low noise and long life. This internal feedback mechanism is effective when the magnetron is operated from a relatively well filtered DC power supply with the cathode heated by back bombardment power alone.
These measurements were made with the magnetron running in a phase locked loop.

Anode current is varies as the external match is varied.

Pushing for Panasonic 2M137

Low noise state associated with low heater power and low anode current
## Amplifier Selection

<table>
<thead>
<tr>
<th></th>
<th>Magnetron</th>
<th>Gyro-Klystron</th>
<th>Klystron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Above ~ 200MHz</td>
<td>above a few GHz</td>
<td>Above ~ 350MHz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>Lower</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Average power</td>
<td>Lower</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Gain</td>
<td>Lower</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Tuneable range</td>
<td>Large</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Instantaneous bandwidth</td>
<td>Smaller</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Slew rate</td>
<td>Smaller</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Noise figure</td>
<td>Higher</td>
<td>Lower</td>
<td></td>
</tr>
<tr>
<td>Best Efficiency L band</td>
<td>~ 90%</td>
<td>ILC ~ 69%</td>
<td></td>
</tr>
<tr>
<td>Best Efficiency X band</td>
<td>~ 50%</td>
<td>50%</td>
<td>XL5 = 40%</td>
</tr>
<tr>
<td>Pushing figure</td>
<td>Significant</td>
<td>Significant</td>
<td></td>
</tr>
<tr>
<td>Pulling figure</td>
<td>Significant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplifier cost</td>
<td>Low</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Modulator &amp; magnet cost</td>
<td>Lower</td>
<td>very high</td>
<td>high</td>
</tr>
</tbody>
</table>
Opportunities

Our conceptual application was for intense proton beams as would be required for a neutrino factory or future spallation sources.

Magnetrons can become an option for intense proton beams where they give significantly greater efficiency than other devices and bring down the lifetime cost of the machine without sacrificing performance and reliability.

The easiest applications are where beam quality is not a key issue.
Permits fast phase control but only slow, full range amplitude control

A substantial development program would be required for a 704 MHz, 880 kW long pulse magnetron

~ -13 dB to -17 dB needed for locking i.e. between 18 kW and 44 kW hence between 42 kW and 16 kW available for fast amplitude control

Could fill cavity with IOT then pulse magnetron when beam arrives
Demonstration of CW 2.45 GHz magnetron driving a specially manufactured superconducting cavity in a vertical test facility at JLab and the control of phase in the presence of microphonics was successful.

First demonstration and performance of an injection locked continuous wave magnetron to phase control a superconducting cavity

A.C. Dexter, G. Burt, R. Carter, I. Tahir, H. Wang, K. Davis, and R. Rimmer,


High-power magnetron transmitter as an RF source for superconducting linear accelerators

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Muons, Inc., Batavia, 60510 IL, USA

Vyacheslav Yakovlev, Brian Chase, Valeri Lebedev, Sergei Nagaitsev, Ralph Pasquinelli, Nikolay Solyak, Kenneth Quinn, and Daniel Wolff,
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Viatcheslav Pavlov,
Budker Institute of Nuclear Physics (BINP), Novosibirsk, 630090, Russia

A concept of a high-power magnetron transmitter based on the vector addition of signals of two injection-locked Continuous Wave (CW) magnetrons, intended to operate within a fast and precise control loop in phase and amplitude, is presented. This transmitter is proposed to drive Superconducting RF (SRF) cavities for intensity-frontier GeV-scale proton/ion linacs, such as the Fermilab Project X 3 GeV CW proton linac or linacs for Accelerator Driven System (ADS) projects. The transmitter consists of two 2-cascade injection-locked magnetrons with outputs combined by a 3-dB hybrid. In such a scheme the phase and power control are accomplished by management of the phase and the phase difference, respectively, in both injection-locked magnetrons, allowing a fast and
Development of a 300 kW CW L-Band Industrial Heating Magnetron

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California Tube Laboratory
Titan Pulse Sciences Division

An industrial heating magnetron operating in L-band (915 MHz) and capable of producing 300 kW of continuous microwave power has been developed and is available for commercial sale. This high average power magnetron design, California Tube Laboratory (CTL) model CWM-300L (Figure 1), is based on the presently-available CTL model CWM-75L, an L-band magnetron that produces 75 kW of continuous microwave power. The 300L magnetron operates at 32 kV and 10 A with a conversion efficiency exceeding 90% when freshly conditioned.

Cooling such high average power output led to a number of design changes involving the waveguide launcher, output dome, and anode block structure. The 300L magnetron can also operate in pulsed mode through the use of a DC “pedestal” voltage of nominally 40 kV on which rides a “pop-up” square waveform voltage of 5 kV. In pulsed mode, operating at 45 kV and 15 A, the 300L can produce 600 kW peak microwave power at 50% duty with efficiencies still in the 90% range, and with pulse repetition frequencies up to 1 kHz (Figure 2). Some problems
Efficiency

For good efficiency need to have slow electrons hitting the anode.

Simple estimate

\[ \eta = 1 - \frac{2mE_{dc}}{eB^2(r_a - r_c)} \]

J.C.Slater, “Microwave Electronics”, Reviews of Modern Physics, Vol 18, No 4, 1946

- High magnetic field important for good efficiency
- Can high efficiency be achieved when magnetron is injection locked?
- Low external Q is needed for stable locking over a useable bandwidth
- Low external Q is good for efficiency

<table>
<thead>
<tr>
<th></th>
<th>800W Cooker</th>
<th>1200W Cooker</th>
<th>SPL 704MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius Cathode</td>
<td>rc (mm)</td>
<td>1.93</td>
<td>2.96</td>
</tr>
<tr>
<td>Radius Anode</td>
<td>ra (mm)</td>
<td>4.35</td>
<td>5.80</td>
</tr>
<tr>
<td>Anode voltage</td>
<td>V</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>~Electric field</td>
<td>E (V/m)</td>
<td>1.65E+06</td>
<td>1.41E+06</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>B (T)</td>
<td>0.185</td>
<td>0.135</td>
</tr>
<tr>
<td>Nominal Efficiency</td>
<td>(\eta)</td>
<td>77.3%</td>
<td>69.1%</td>
</tr>
</tbody>
</table>
PIC Code Modelling

Have used VORPAL and MAGIC to simulate magnetrons.
Takes a huge amount of time to get a single operating point.
Gets impedance incorrect for efficient cooker magnetrons.
Prefer to assume RF field and compute trajectories in a self consistent d.c. field.
VORPAL model of 2M137 Panasonic magnetron
Magnetron Start Up

• No RF seeding /RF injection has been used in previous slide.
• Spoke growth requires noise. The noise comes from mesh irregularities and random emission.
• Start up time is mesh dependent.
• Start also requires sufficient charge to collect in cathode anode gap.
• Without random emission and mesh irregularity all electrons return to cathode and the magnetron does not start.
• Once the rotating charge has a certain density and extent, the spokes form very quickly.
• A lot of time is wasted with PIC models waiting for the magnetron to start.
• Conversely a problem with steady state models is that one does not necessarily know how to get to the operating point that was modelled.
Magnetron Operation Panasonic 2M137

Results from a self consistent model with a coiled cathode

Electrons can leave from any point on coil hence emission points are within the inner circle marking the outside radius of the cathode

Electrons can spiral between turns contributing to space charge at the cathode.

If the electrons become synchronous with the RF then they move to the anode in about 5 arcs.

Most electrons return to the cathode.
Orbits in high efficiency 2.45 GHz cooker design

\[ B = 2.2T, V = 4000, I_A = 1.13A, V_{RF} = 2450V, P = 3.86kW, \text{Eff} = 86\%, \text{Solid Cathode 1880K} \]
Field in high efficiency 2.45 GHz cooker design

Efficiency peaks as tops of cusps coincide with anode.

Calculations are not fully realistic as to change the RF voltage one has to change external Q and this changes the frequency.

At this operating point the field at cathode is just negative. Field at cathode becomes positive as cathode temperature increases or anode current decreases. To get a stable calculation mesh size near cathode ~ 2 microns.
Orbits for 1 MW 704 MHz design

An efficient orbit should have no loop, electronic efficiency prediction ~ 96%
Reflection Amplifier Controllability

1. Phase of output follows the phase of the input signal
2. Phase shift through magnetron depends on difference between input frequency and the magnetrons natural frequency
3. Output power has minimal dependence on input signal power (Should add)
4. Phase shift through magnetron depends on input signal power
5. There is a time constant associated with the output phase following the input phase

Magnetron frequency and output vary together as a consequence of

1. Varying the magnetic field
2. Varying the anode current (pushing)
3. Varying the reflected power (pulling)
Frequency Stabilisation with Phase Lock Loop (PPL)

- Water Load
- Loop Coupler
- Frequency Divider / N
- Divider / R
- Phase - Freq Detector & Charge Pump
- Micro-Controller
- ADF 4113
- Loop Filter
- Low Pass Filter 8 kHz cut-off
- 3 Stub Tuner
- High Voltage Transformer
- Power supply: 325 V DC with 5% 100 Hz ripple
- 40kHz Chopper
- Pulse Width Modulator SG 2525
- 1.5 kW Power
PLL Board Layout
Spectrum with PLL frequency control

Heater Power = 4.2W
Bandwidth ~ 100 kHz
Magnetron Layout for Locking
The performance of a magnetron in the control loop of a phase locked accelerator cavity depends on its bandwidth. Its bandwidth determines how quickly it can respond to a new required phase.
Frequency Shift Keying

Lower trace is output from double-balance mixer when magnetron injection signal is switched from 2.452 to 2.453 GHz at a rate of 250 kb/s (upper trace) and referenced to 2.451 GHz.
Response as function of heater power

Mismatch ~13% reflected power at 100 deg towards load.

Input wave
- 8 W heater
- 15 W heater
- 36 W heater
- 43 W heater

Matched.
Phase Control in Warm Cavity

- Water Load
- 2 Stub Tuner 2
- Loop Coupler
- 1W Amplifier
- IQ Modulator (Amplitude & phase shifter)
- Divider / R
- Frequency Divider / N
- Micro-Controller
- 10 MHz TCXO 1ppm
- Loop Filter
- Divider / N
- Phase - Freq Detector & Charge Pump
- ADF 4113
- Loop Filter
- Digital Phase Detector 1.3GHz
- Oscilloscope
- Oscilloscope
- LP Filter 8 kHz cut-off
- Pulse Width Modulator SG 2525
- 1.5 kW Power Supply
- High Voltage Transformer
- 40kHz Chopper
- 2.3 - 2.6 GHz PLL Oscillator ADF4113 + VCO
- 10 MHz TCXO 1ppm
- 3 Stub Tuner 1
- Loop Coupler
- Circulator 1
- Water Load
- 10 Vane Magnetron
- 1.5 kW Power Supply
- 325 V DC + 5% 100 Hz ripple
- Power supply ripple
- Magnetron phase no LLRF
- Magnetron phase with LLRF

pk-pk 26°

pk-pk 1.2°
Prospects

• Intense beams in user facilities need to be generated efficiently.
• Developing a new HPRF source is expensive and comparison to available sources is difficult before development is mature.
• Would not use magnetron for a superconducting linac if klystron affordable.
• Universities will continue to explore new concepts.
• Need accelerator labs to explore new devices at accelerator test stands to have any chance of new devices becoming feasible alternatives.
• Future accelerators constrained on cost so research on efficient low cost sources is worthwhile.
SCRF cavity powered with magnetron

Injection but magnetron off

Injection + magnetron on

Injection + magnetron on + control

Injection + magnetron on

Cavity phase error (degrees)