Magnetrons for accelerators

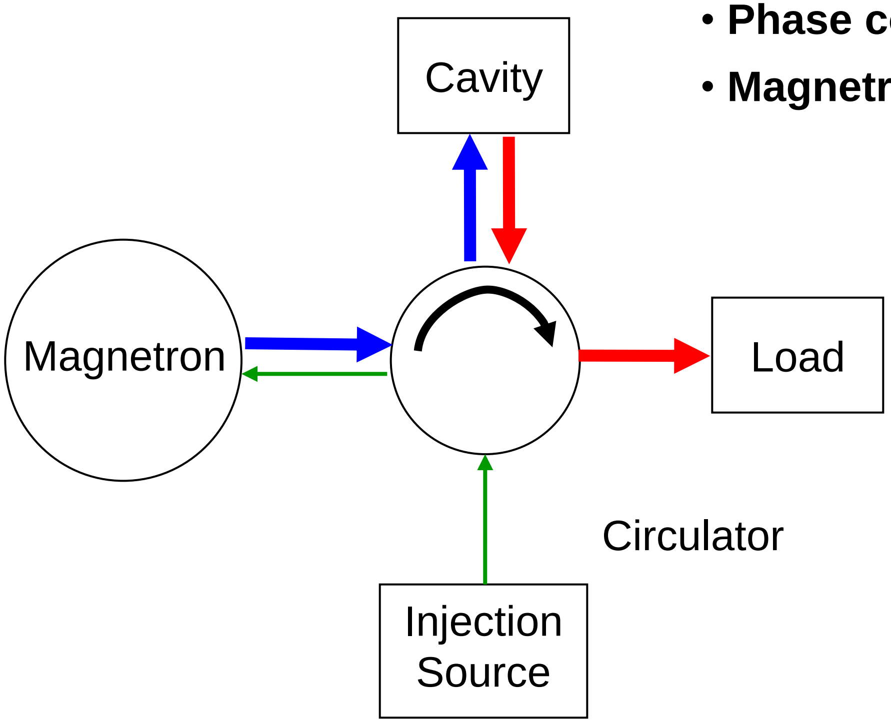
Amos Dexter

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,"
IRE Transactions on Electron Devices, vol. ED-8, Nov 1961

H.L. Thal and R.G. Lock, "Locking of magnetrons by an injected r.f. signal",
IEEE Trans. MTT, vol. 13, 1965

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.

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

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

Benford J., Sze H., Woo W., Smith R., and Harteneck B., **"Phase locking of relativistic magnetrons"** *Phys. Rev.Lett.*, vol. 62, no. 4, pp. 969, 1989.

Treado T. A., Hansen T. A., and Jenkins D.J. **"Power-combining and injection locking magnetrons for accelerator applications,"** *Proc IEEE Particle Accelerator Conf.*, San Francisco, CA 1991.

Chen, S. C.; Bekefi, G.; Temkin, R. J. **" Injection Locking of a Long-Pulse Relativistic Magnetron"** *PAC* 1991

Treado, T. A.; Brown, P. D.; Hansen, T. A.; Aiguier, D. J. **" Phase locking of two long-pulse, high-power magnetrons"** , *IEEE Trans. Plasma Science,* vol 22, p616-625, 1994

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

Low Noise State for Cooker Magnetrons

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 slot ted 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.

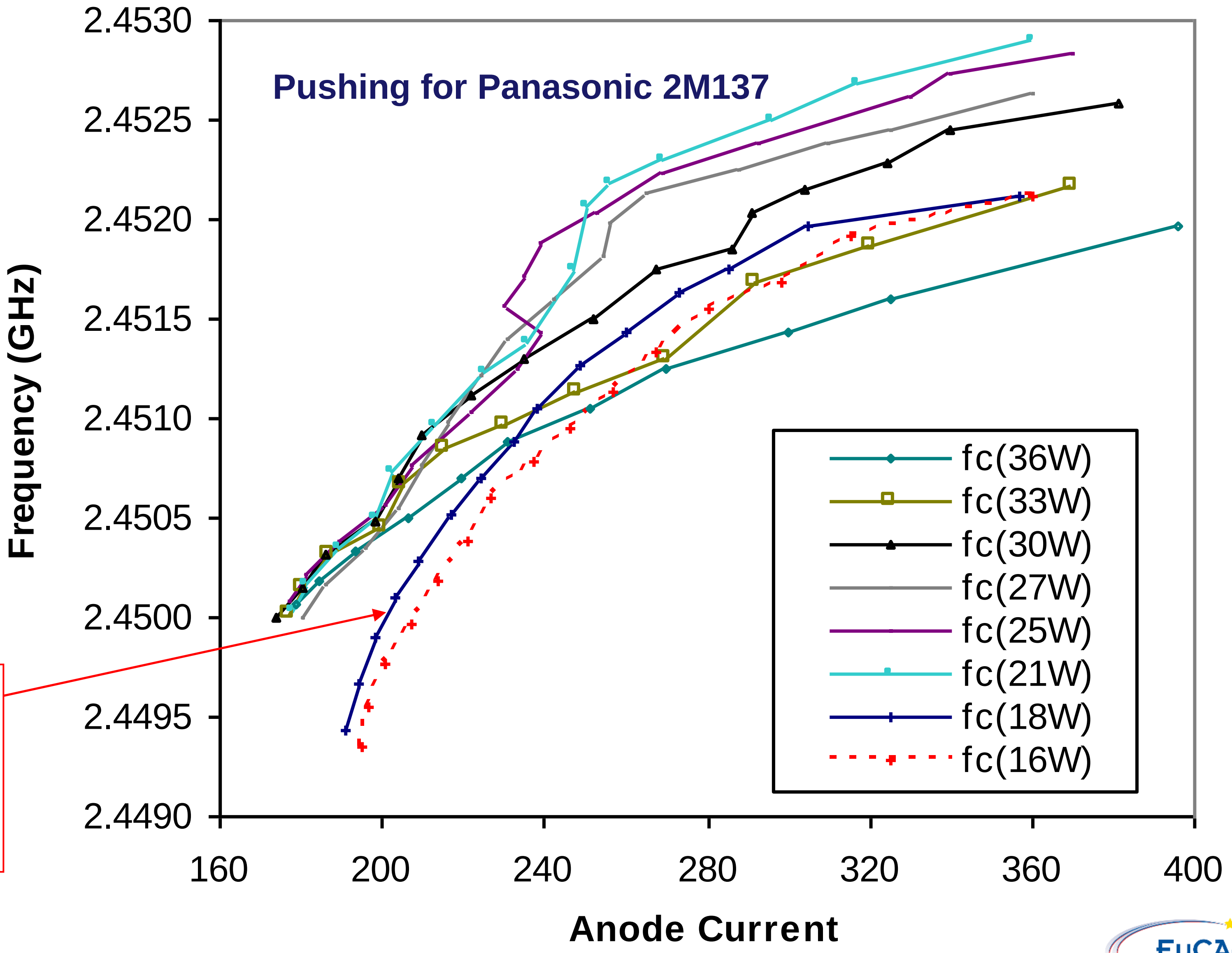
The low noise and long life properties are associated with a feedback mechanism internal to the magnetron that hold s the emission capabilities of the cathode to those levels consistent with both low noise and Jong life. This internal feedback mechanism is effective when the magnetron is operated from a relatively well filtered DC power supply with the cathode heated by back bombardment power alone.

APPLIED MICROWAVE Summer 1990

Pushing Curves and Low Noise State

These measurements were made with the magnetron running in a phase locked loop.

Anode current is varies as the external match is varied.



Low noise state associated with low heater power and low anode current

Amplifier Selection

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

Opportunities

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

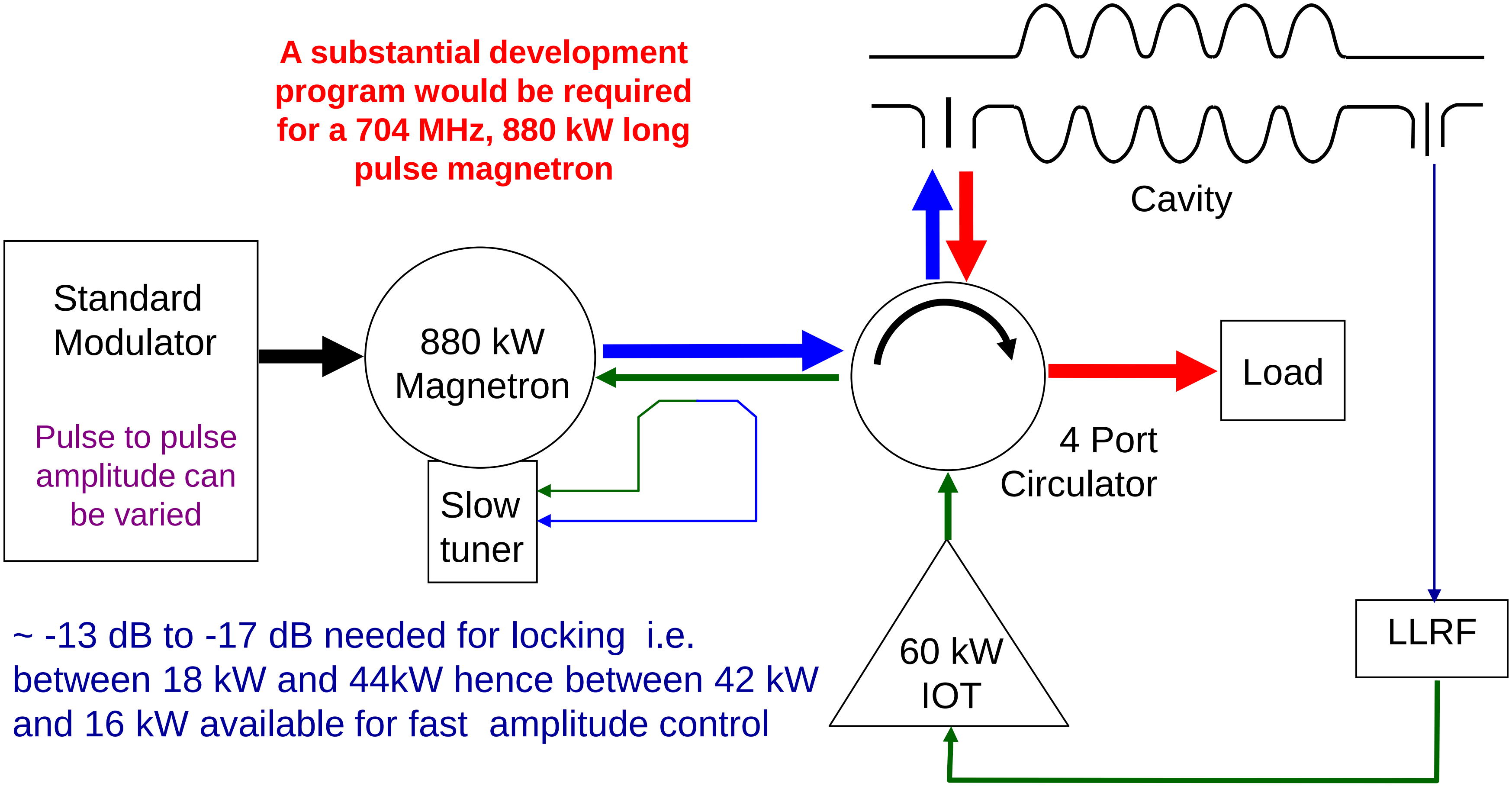
Magnetrons can become an option for intense proton beams where they give significantly greater efficiency than other devices and bring down the lifetime cost of the machine without sacrificing performance and reliability.

The easiest applications are where beam quality is not a key issue.

A Magnetron Solution for SPL?

https://indico.cern.ch/event/63935/session/1/contribution/73

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 44kW hence between 42 kW and 16 kW available for fast amplitude control

Could fill cavity with IOT then pulse magnetron when beam arrives

Magnetron Exciting Superconducting cavity

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,
Physical Review Special Topics: Accelerators and Beams, Vol. 14, No. 3, 17.03.2011, p. 032001.

http://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.14.032001

FERMILAB-PUB-13-315-AD-TD

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

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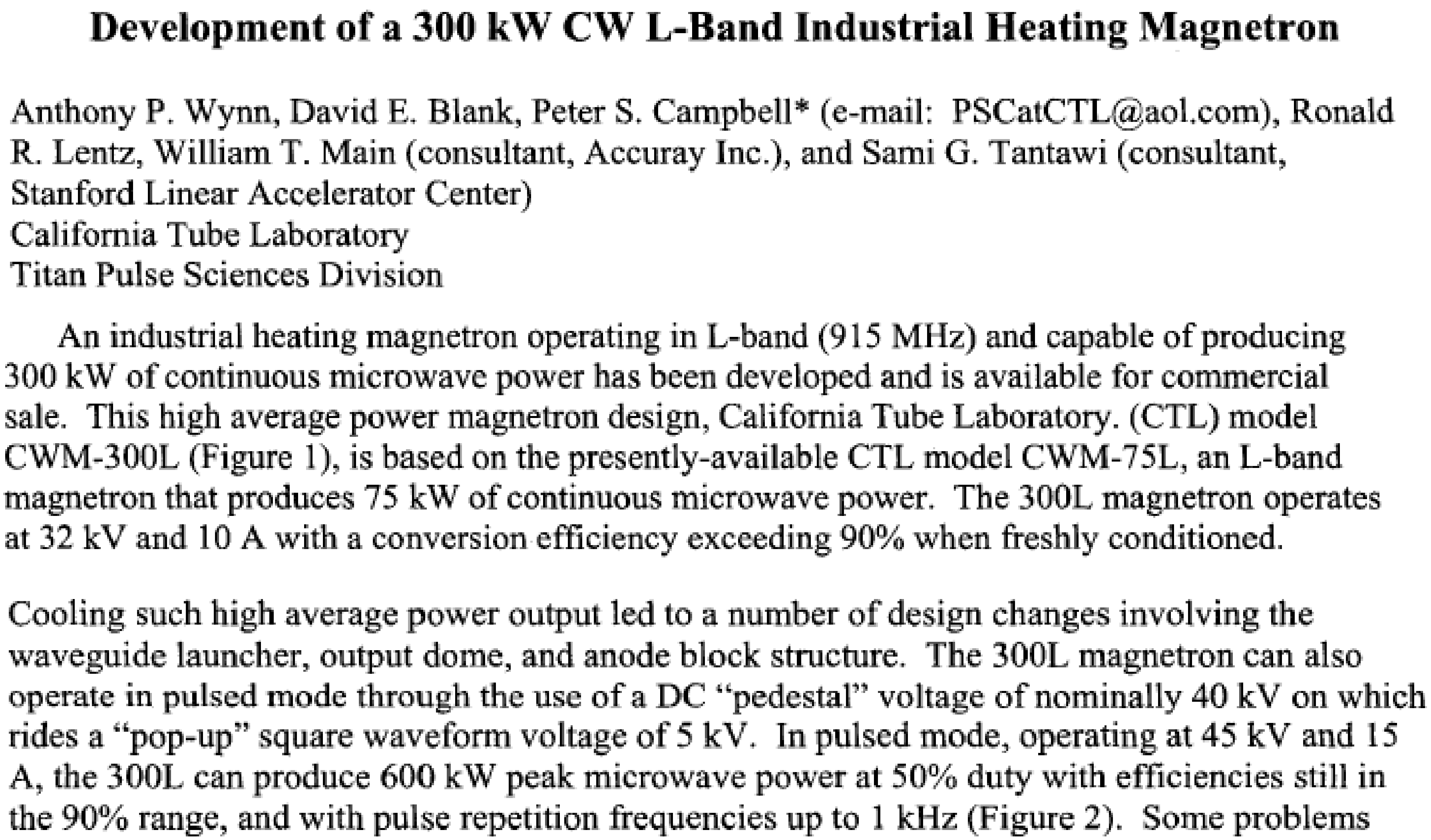
Muons, Inc., Batavia, 60510 IL, USA

Vyacheslav Yakovlev, Brian Chase, Valeri Lebedev, Sergei Nagaitsev, Ralph Pasquinelli, Nikolay Solyak, Kenneth Quinn, and Daniel Wolff,
Fermilab, Batavia, 60510 IL, USA

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

High Efficiency Proven at L Band



Development of a 300 kW CW L-Band Industrial Heating Magnetron

Anthony P. Wynn, David E. Blank, Peter S. Campbell* (e-mail: PSCatCTL@aol.com), Ronald R. Lentz, William T. Main (consultant, Accuray Inc.), and Sami G. Tantawi (consultant, Stanford Linear Accelerator Center)
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.

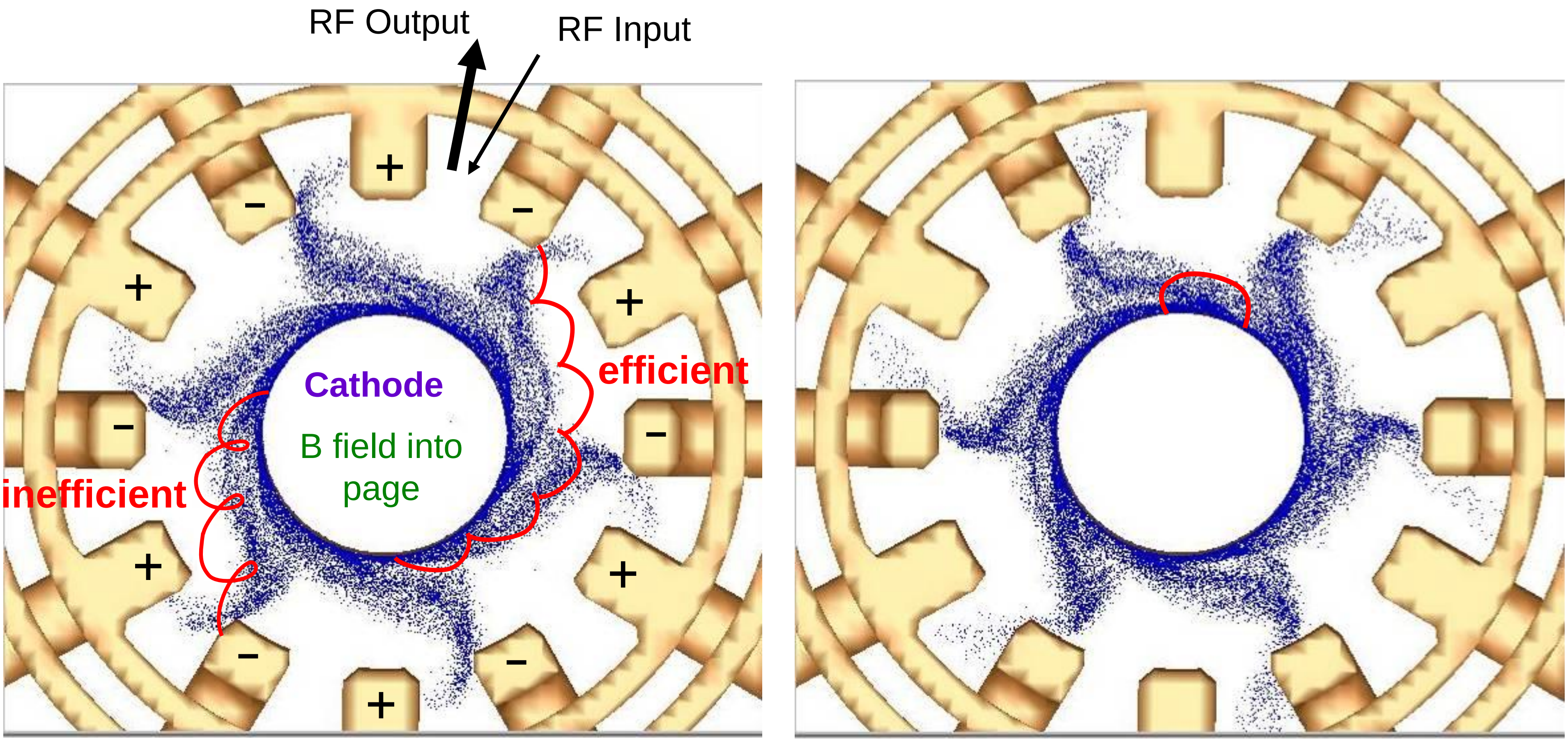
Simple estimate $$\eta = 1 - \frac{2mE_{dc}}{eB^2(r_a - r_c)}$$

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

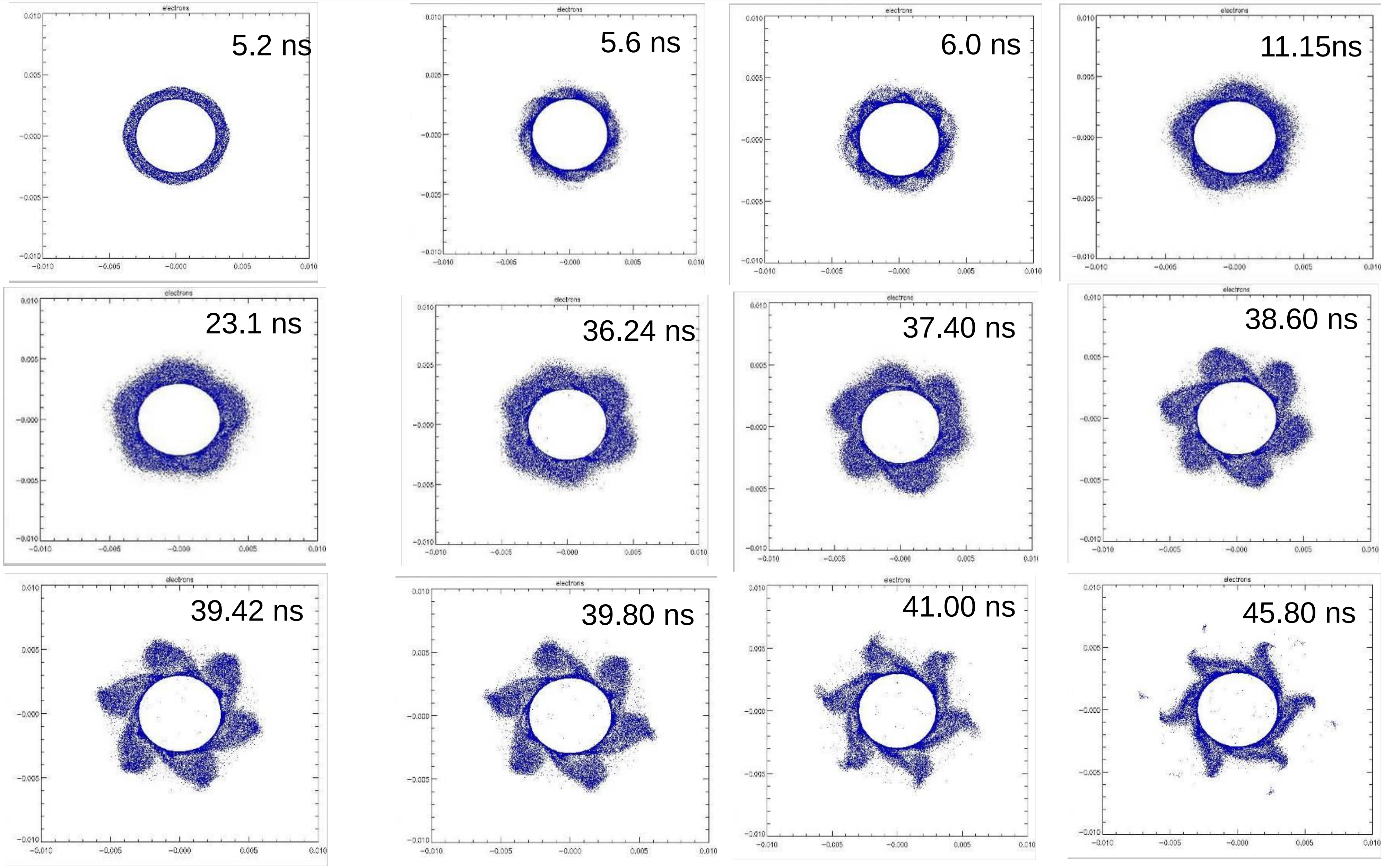
		800W Cooker	1200W Cooker	SPL 704MHz
Radius Cathode	rc (mm)	1.93	2.96	17.74
Radius Anode	ra (mm)	4.35	5.80	24.01
Anode voltage	V	4000	4000	41876
~Electric field	E (V/m)	1.65E+06	1.41E+06	6.68E+06
Magnetic field	B (T)	0.185	0.135	0.413
Nominal Efficiency	η	77.3%	69.1%	92.9%

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

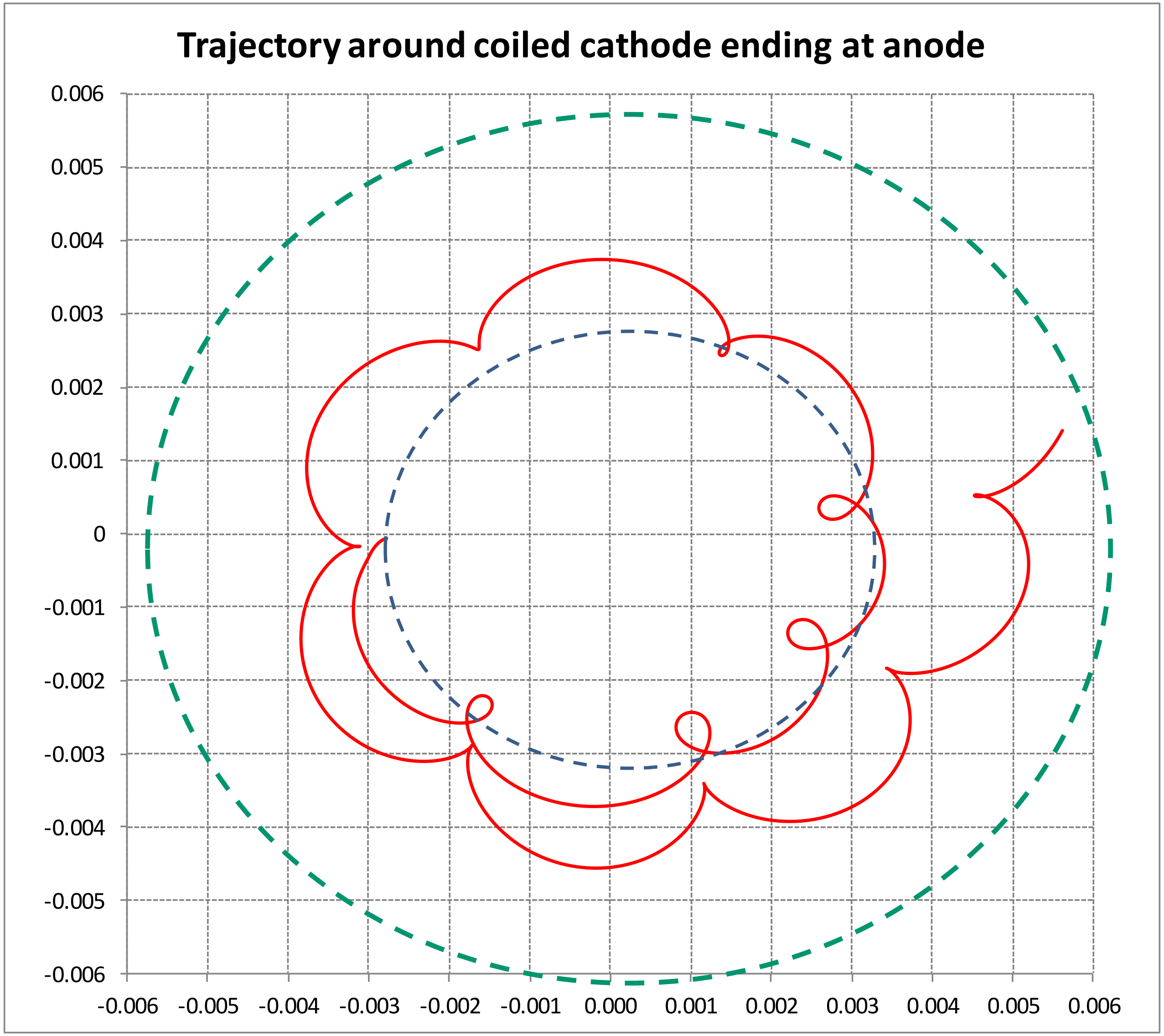
Results from a self consistent model with a coiled cathode

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

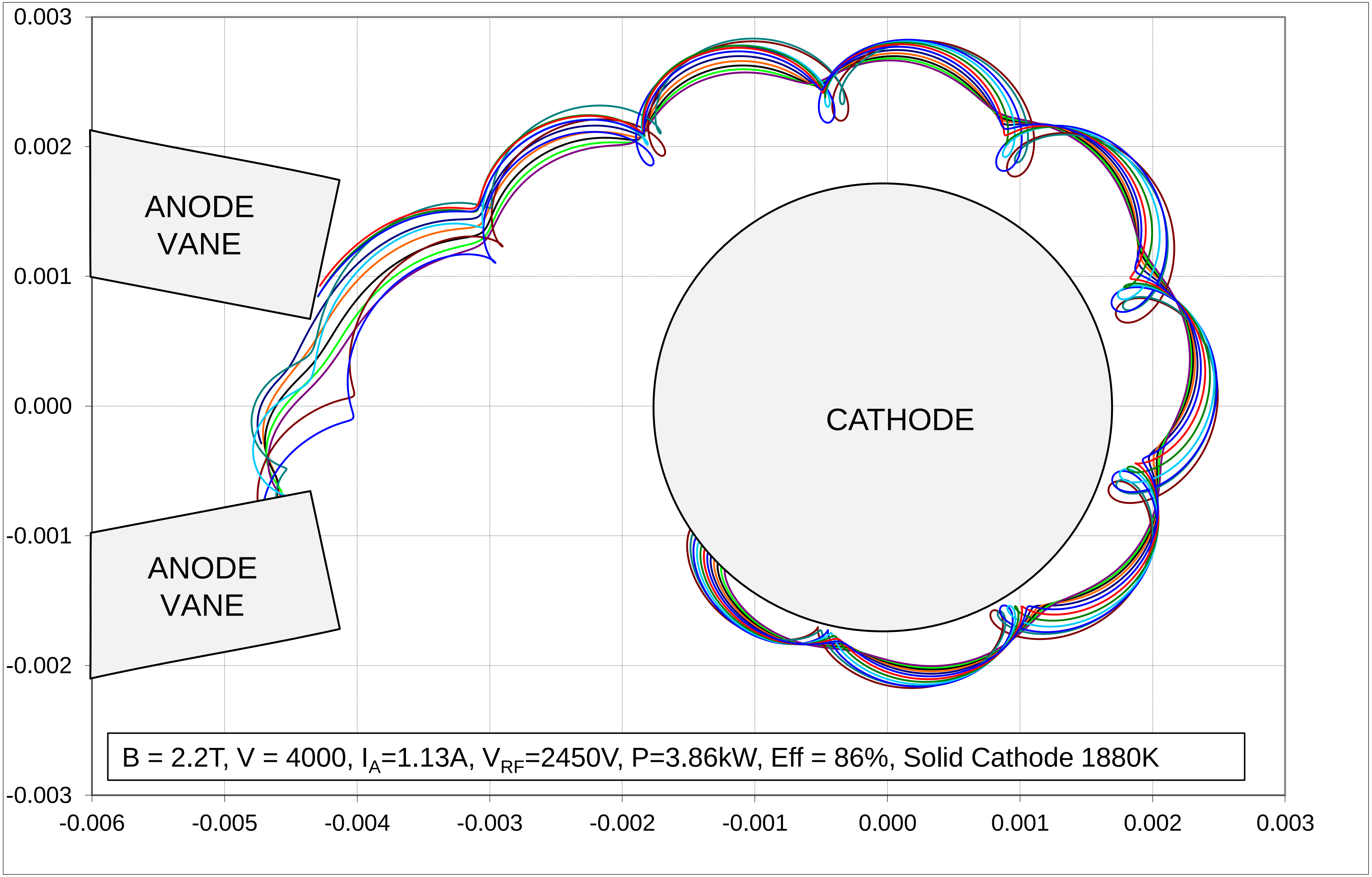
Electrons can spiral between turns contributing to space charge at the cathode.

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

Most electrons return to the cathode.

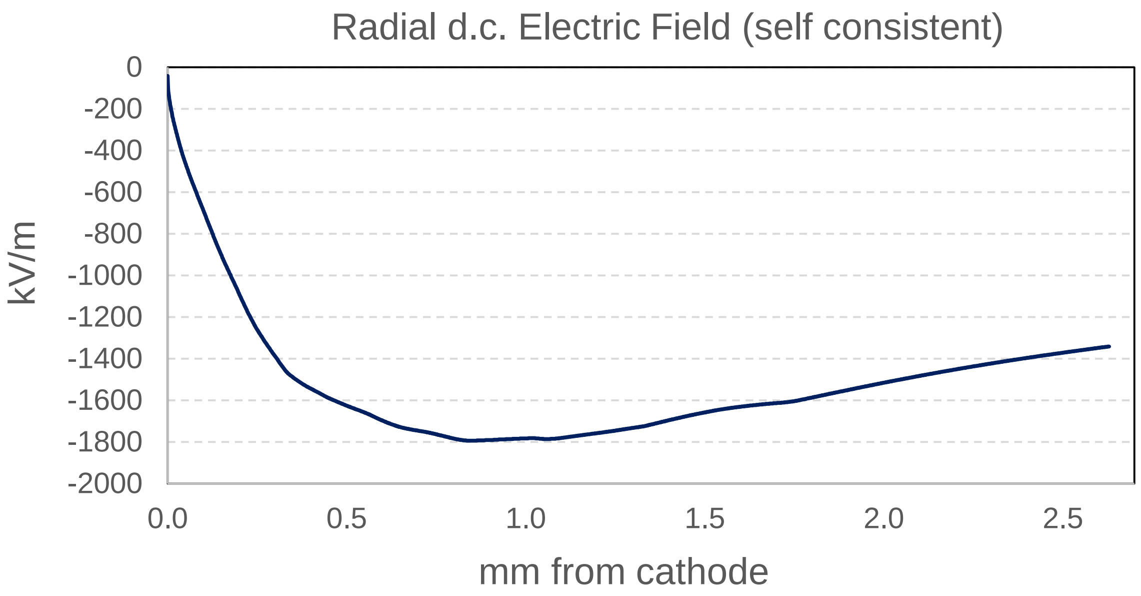


Orbits in high efficiency 2.45 GHz cooker design

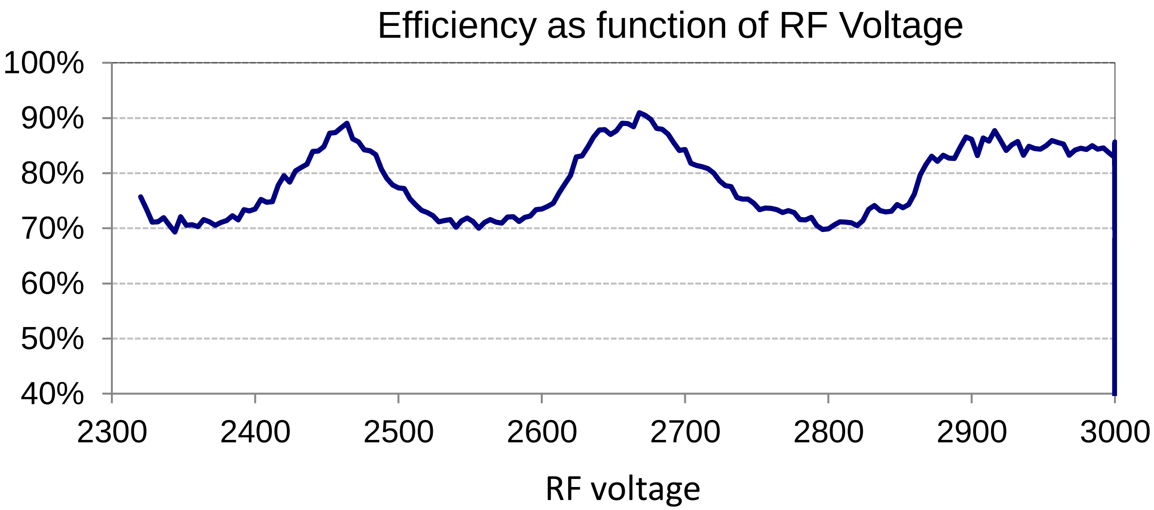


B = 2.2T, V = 4000, I_A=1.13A, V_{RF}=2450V, P=3.86kW, Eff = 86%, Solid Cathode 1880K

Field in high efficiency 2.45 GHz cooker design



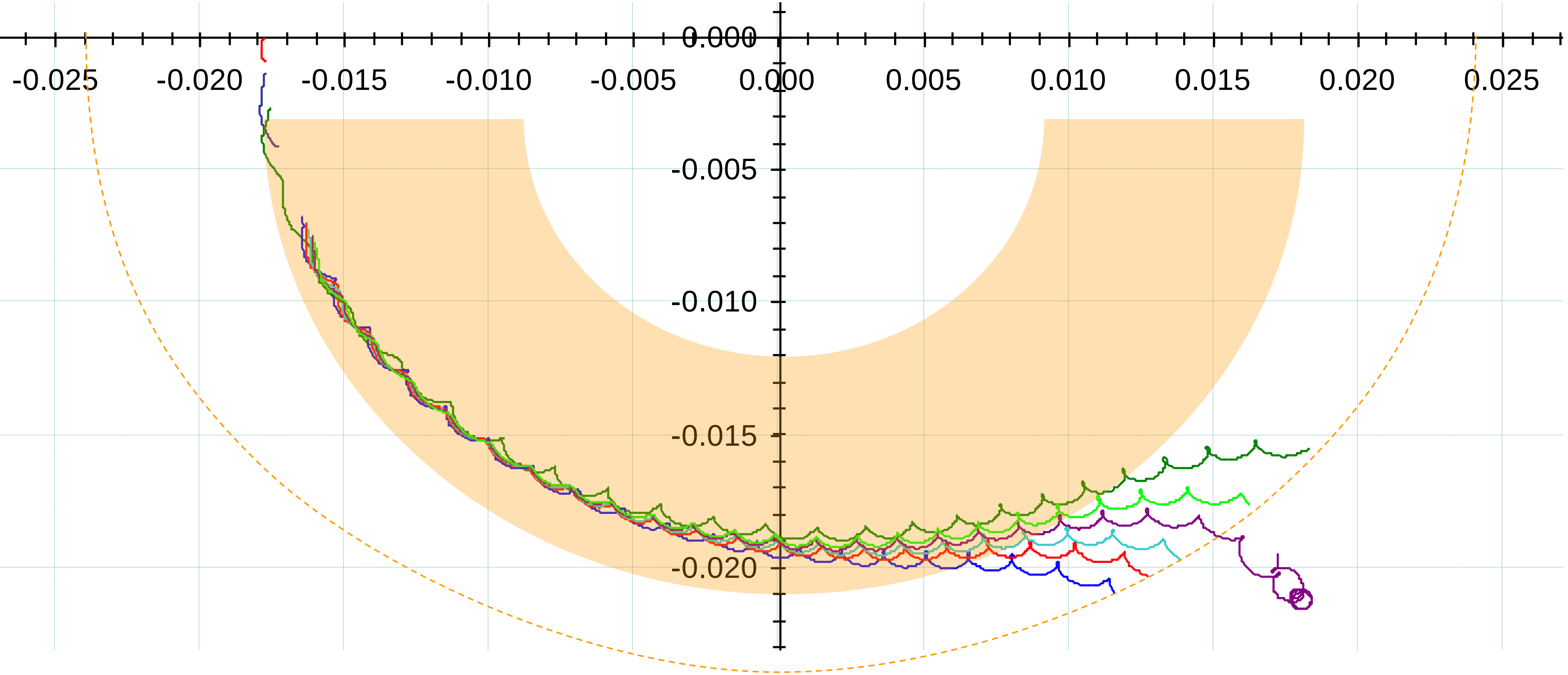
At this operating point the field at cathode is just negative.
Field at cathode becomes positive as cathode temperature increases or anode current decreases. To get a stable calculation mesh size near cathode ~ 2 microns



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

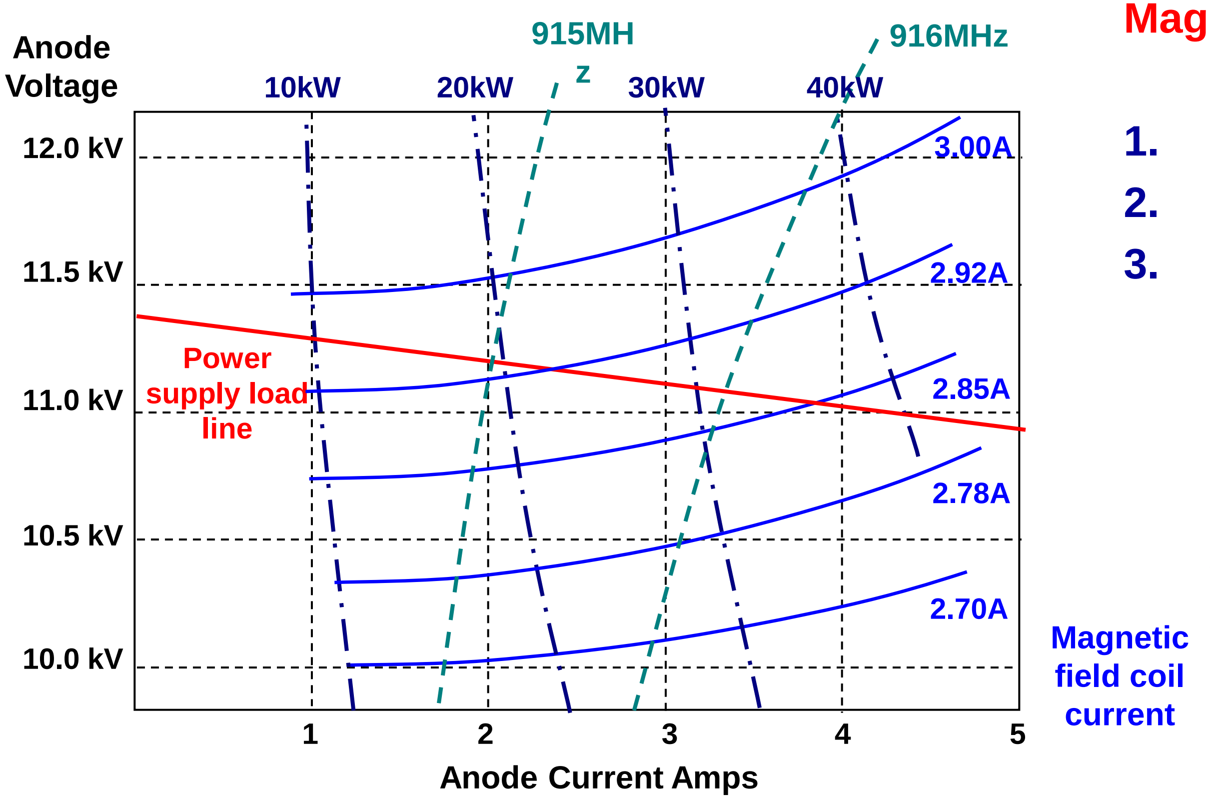
Orbits for 1 MW 704 MHz design



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

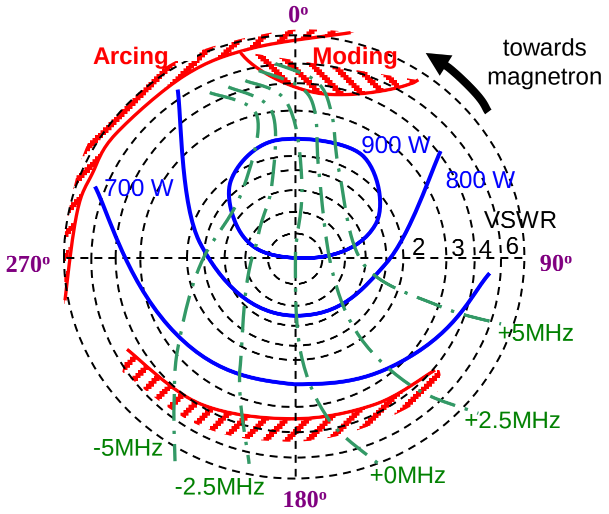
Reflection Amplifier Controllability

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

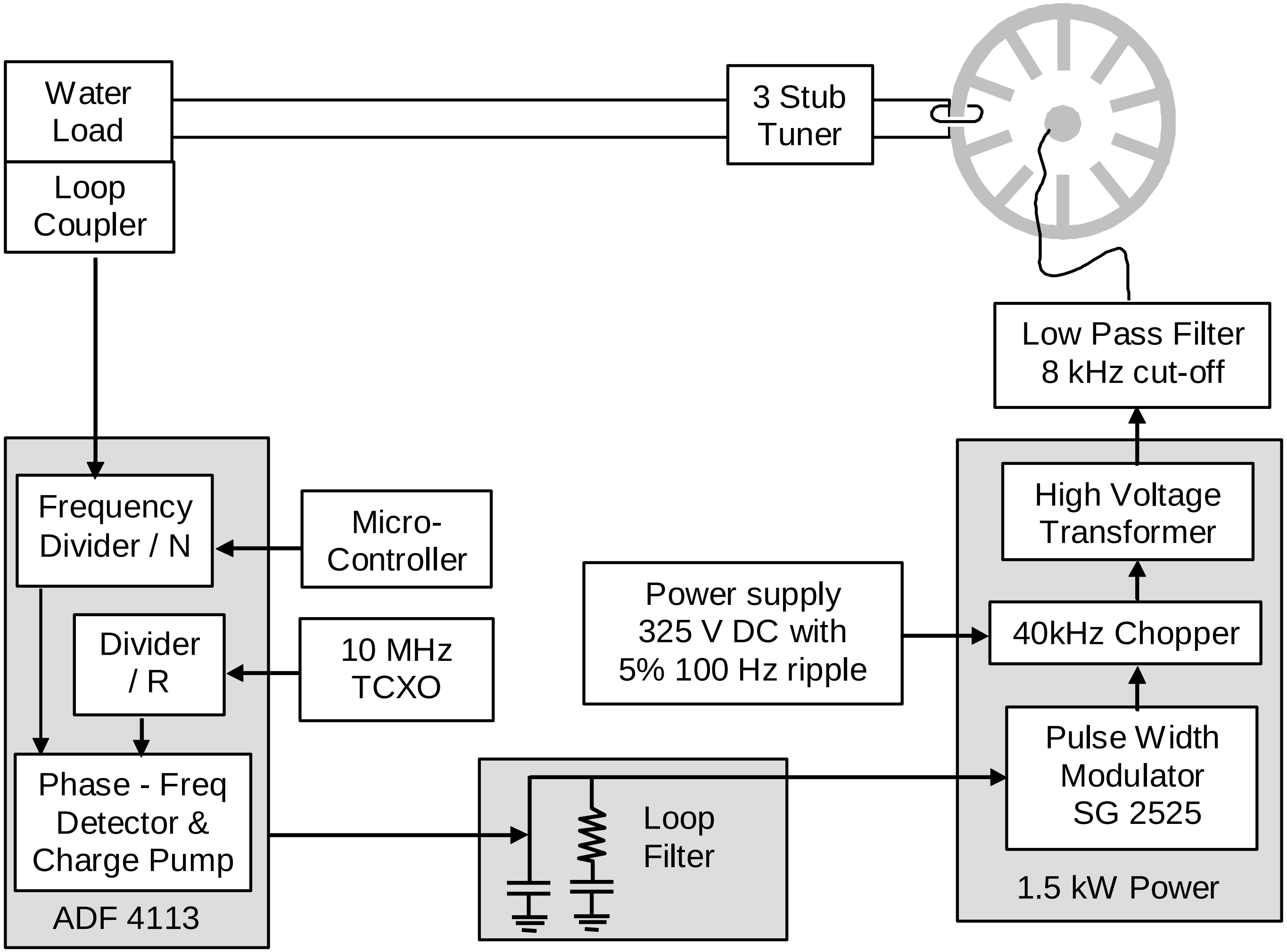


Magnetron frequency and output vary together as a consequence of

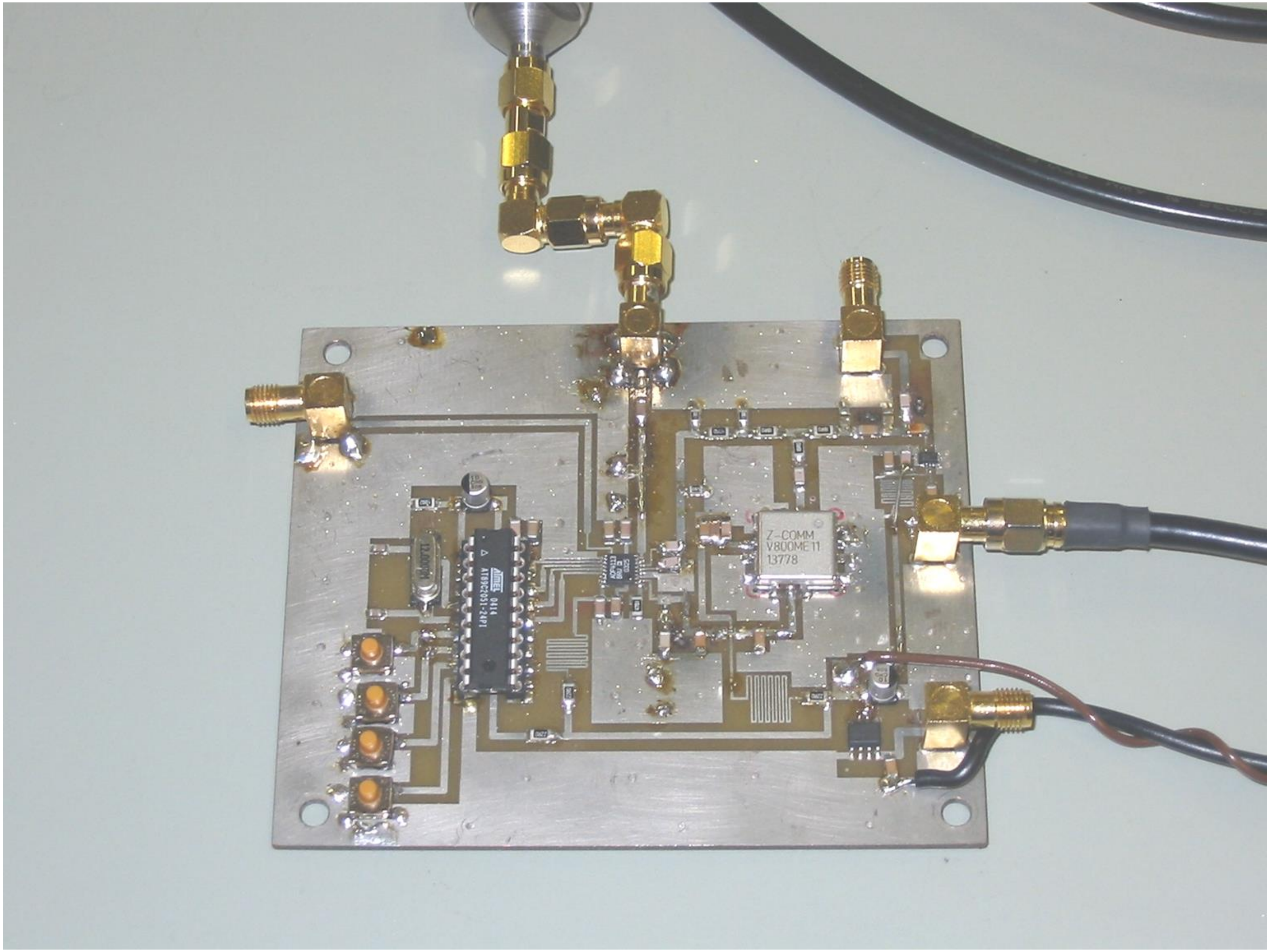
1. Varying the magnetic field
2. Varying the anode current (pushing)
3. Varying the reflected power (pulling)



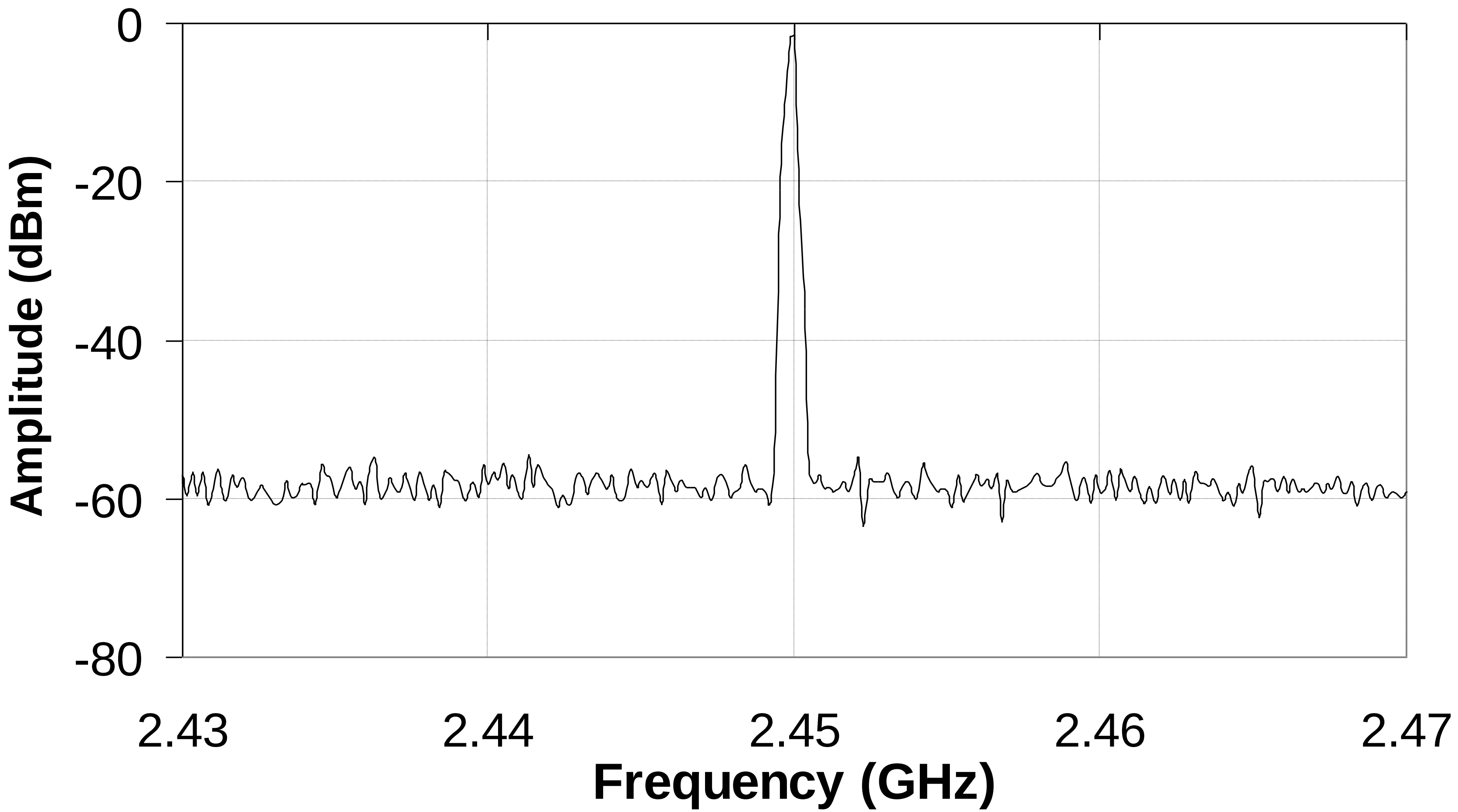
Frequency Stabilisation with Phase Lock Loop (PPL)



PLL Board Layout



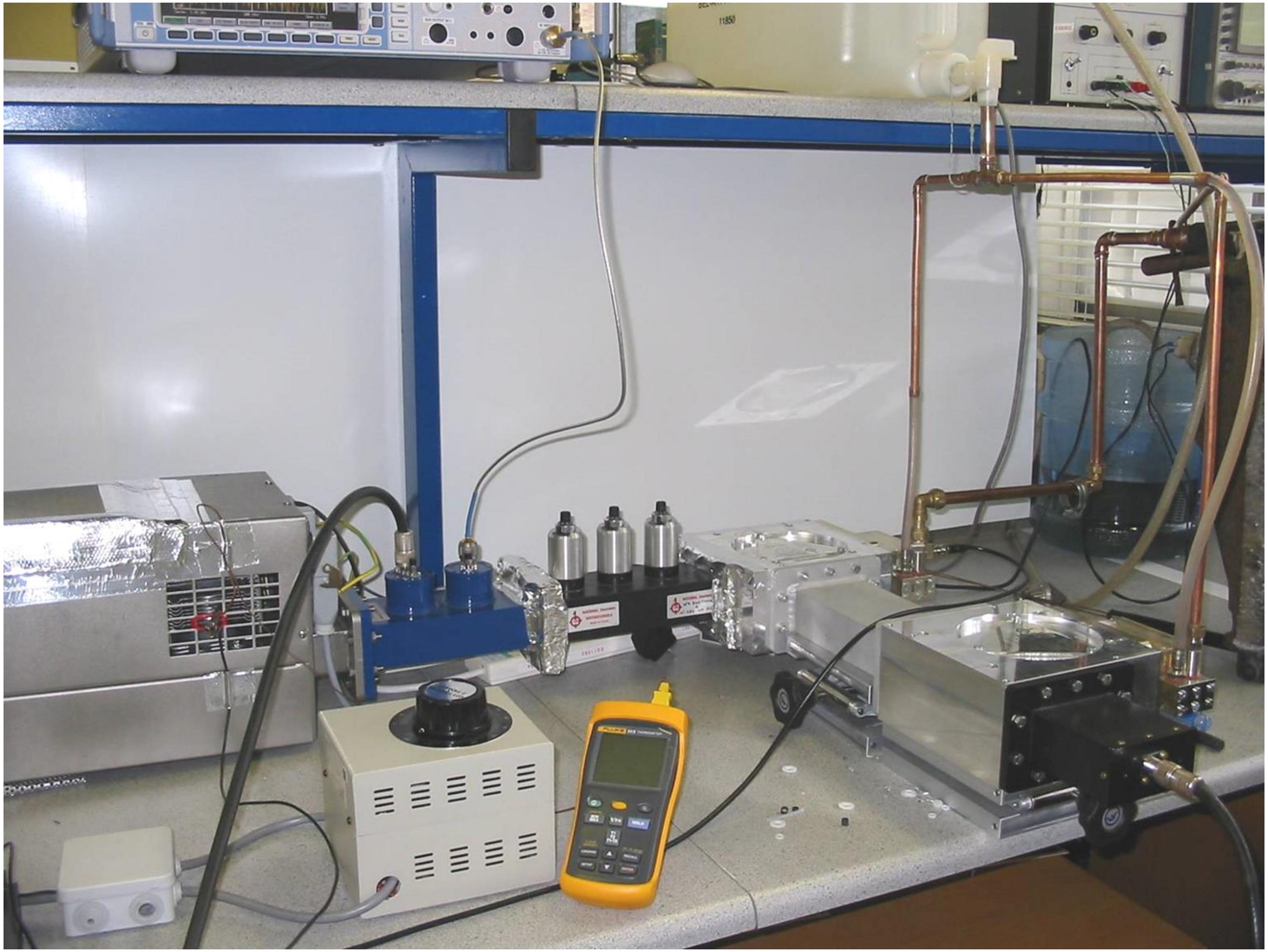
Spectrum with PLL frequency control



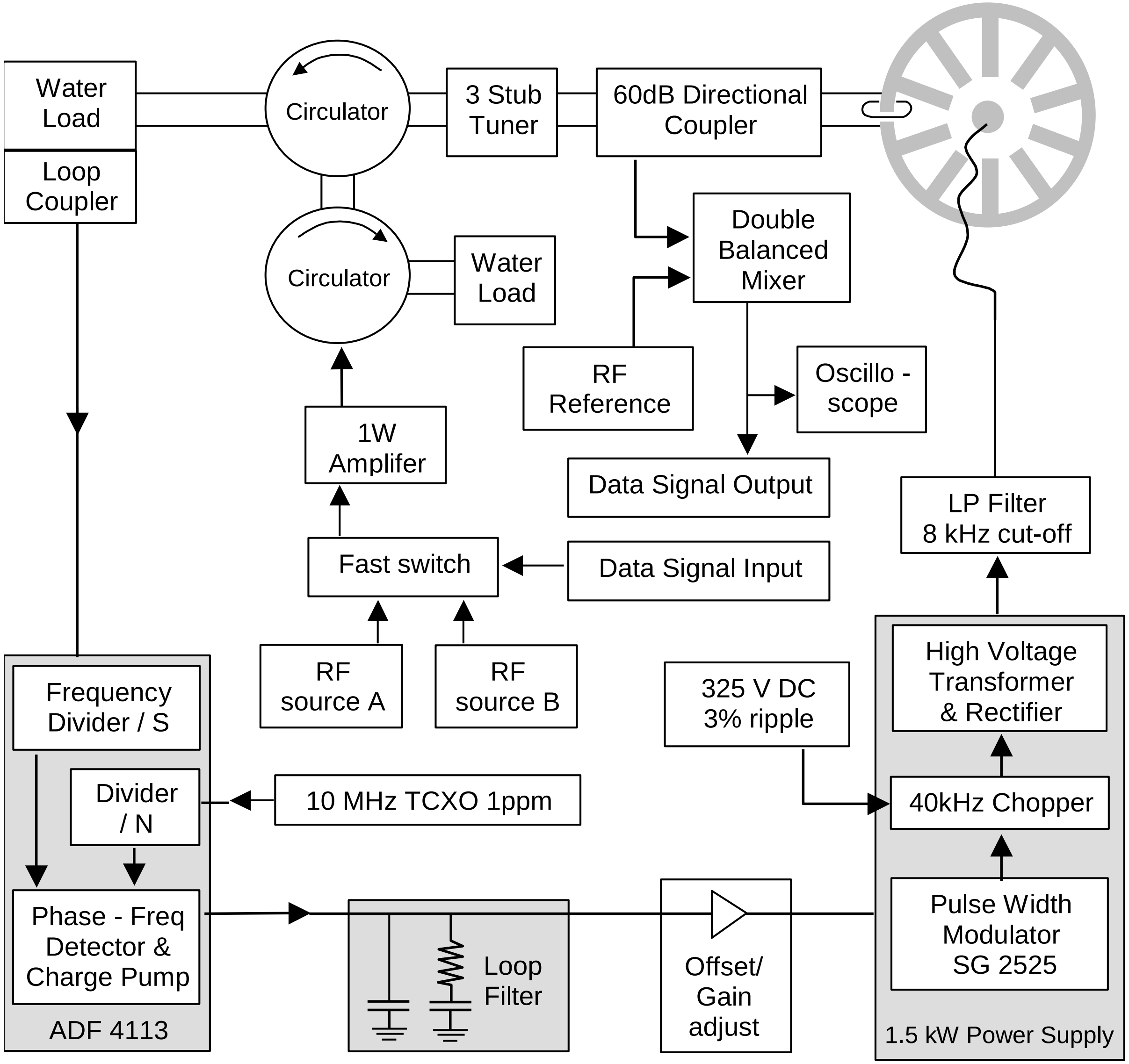
Heater Power = 4.2W

Bandwidth ~ 100 kHz

Magnetron Layout for Locking



Phase & Freq Shift Keying Injection Locked Magnetron



Water Load

Loop Coupler

Circulator

3 Stub Tuner

60dB Directional Coupler

Circulator

Water Load

Double Balanced Mixer

RF Reference

Oscillo - scope

1W Amplifer

Data Signal Output

LP Filter
8 kHz cut-off

Fast switch

Data Signal Input

RF source A

RF source B

Frequency Divider / S

Divider / N

Phase - Freq Detector & Charge Pump

ADF 4113

10 MHz TCXO 1ppm

325 V DC
3% ripple

High Voltage Transformer & Rectifier

40kHz Chopper

Pulse Width Modulator
SG 2525

1.5 kW Power Supply

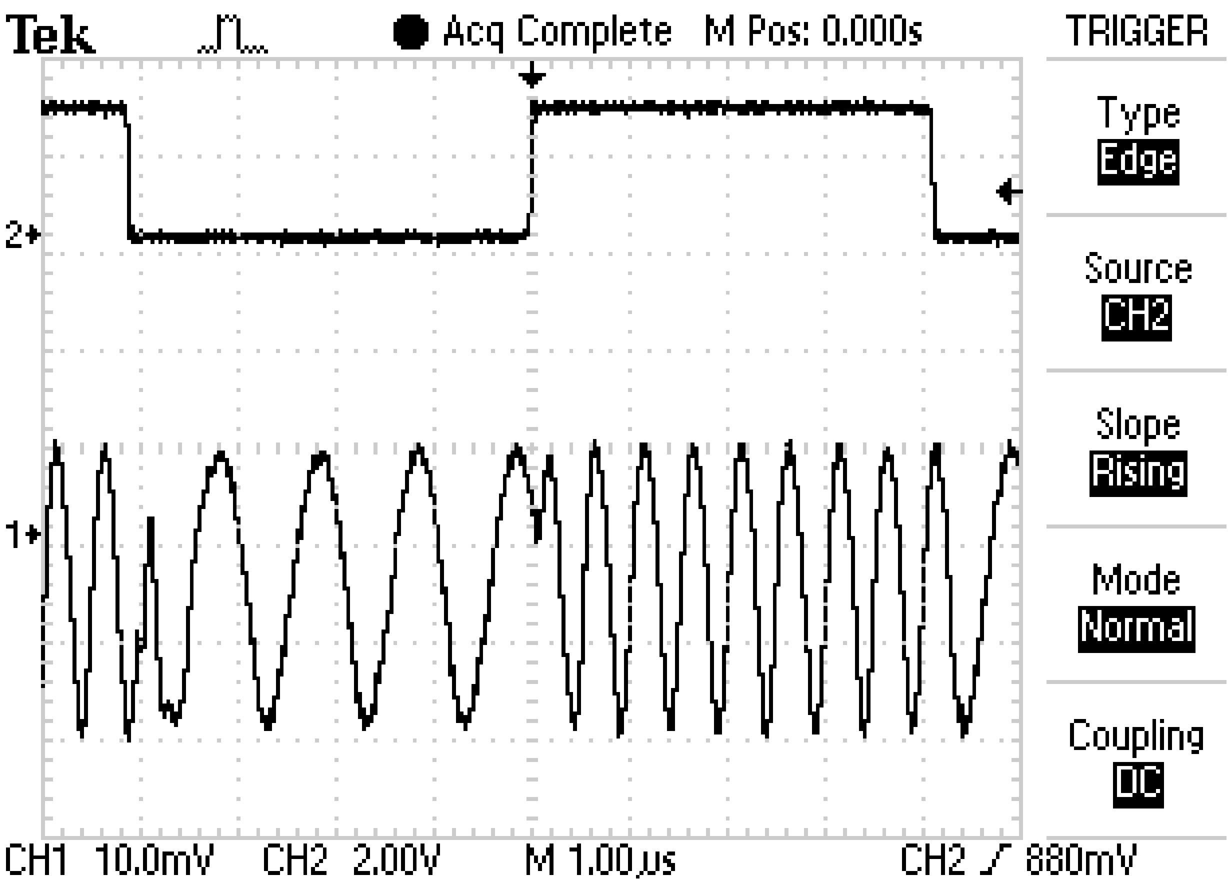
Loop Filter

Offset/ Gain adjust

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



Tek Acq Complete M Pos: 0.000s

TRIGGER

Type Edge

Source CH2

Slope Rising

Mode Normal

Coupling DC

CH1 10.0mV CH2 2.00V M 1.00µs CH2 ∕ 880mV

Input to pin diode

Output from double balanced mixer after mixing with 3rd frequency

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

Matched.

← Input wave

8 W heater

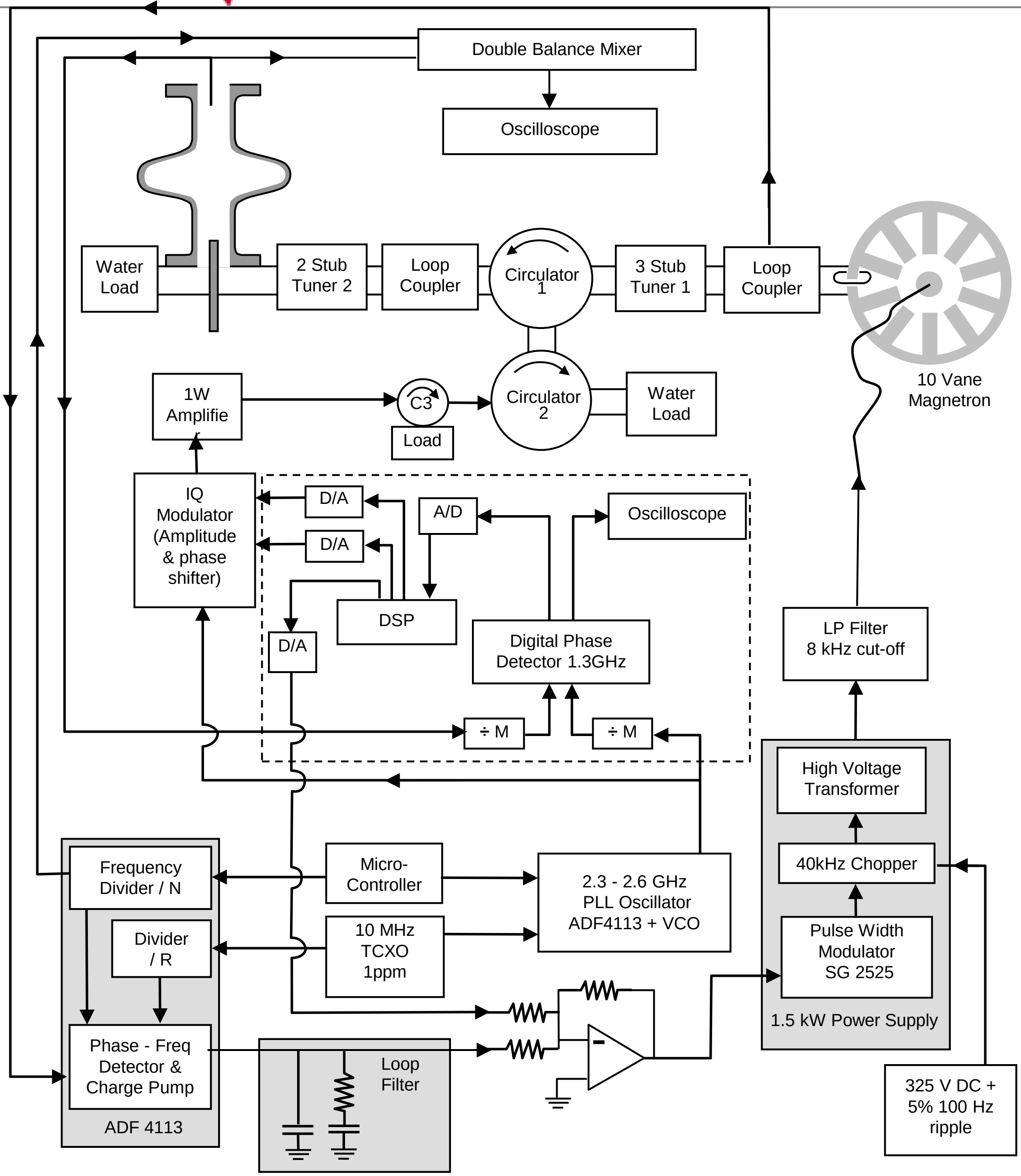
15 W heater

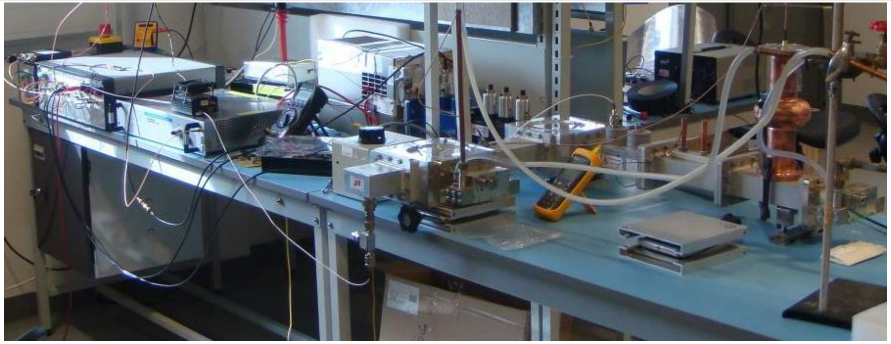
36 W heater

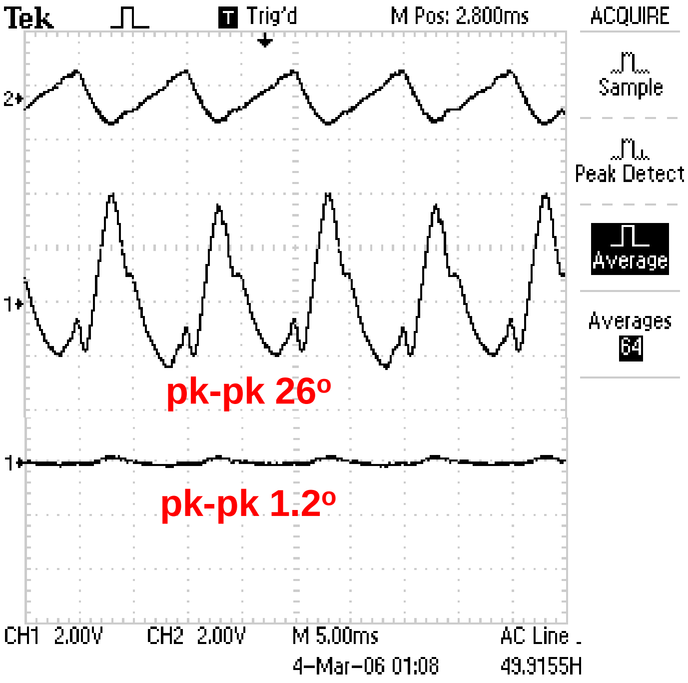
43 W heater

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

Phase Control in Warm Cavity







Power supply ripple

Magnetron phase no LLRF

pk-pk 26^o

Magnetron phase with LLRF

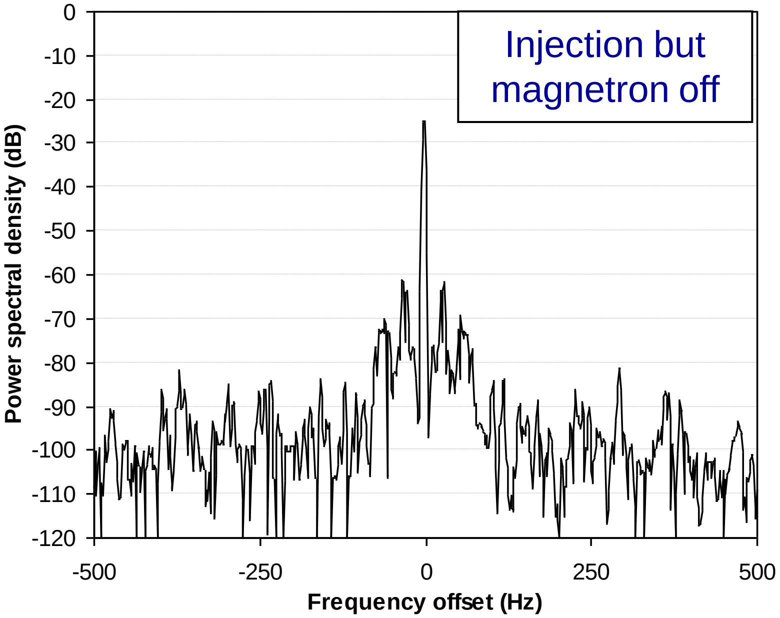
pk-pk 1.2^o

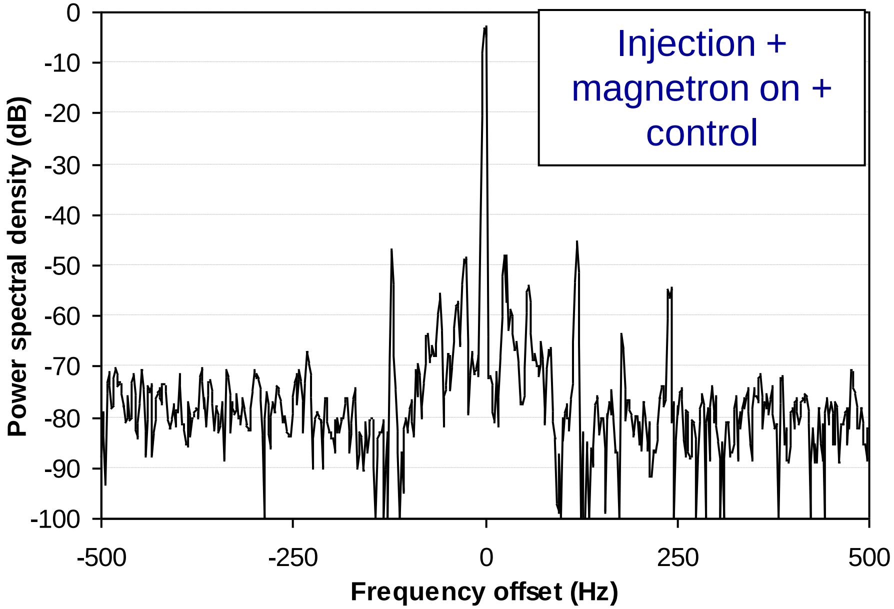
Prospects

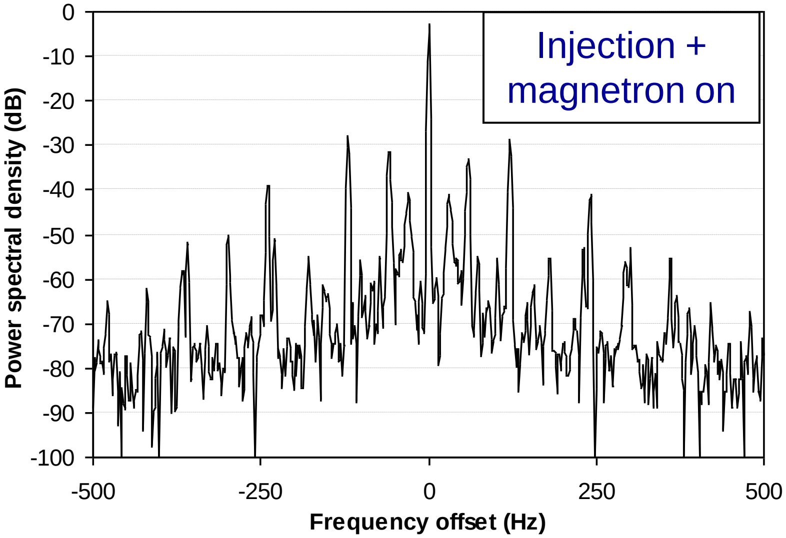
- Intense beams in user facilities need to be generated efficiently.
- Developing a new HPRF source is expensive and comparison to available sources is difficult before development is mature.
- Would not use magnetron for a superconducting linac if klystron affordable.
- Universities will continue to 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.

Extra Slides

SCRF cavity powered with magnetron


Injection but magnetron off


Injection + magnetron on + control


Injection + magnetron on