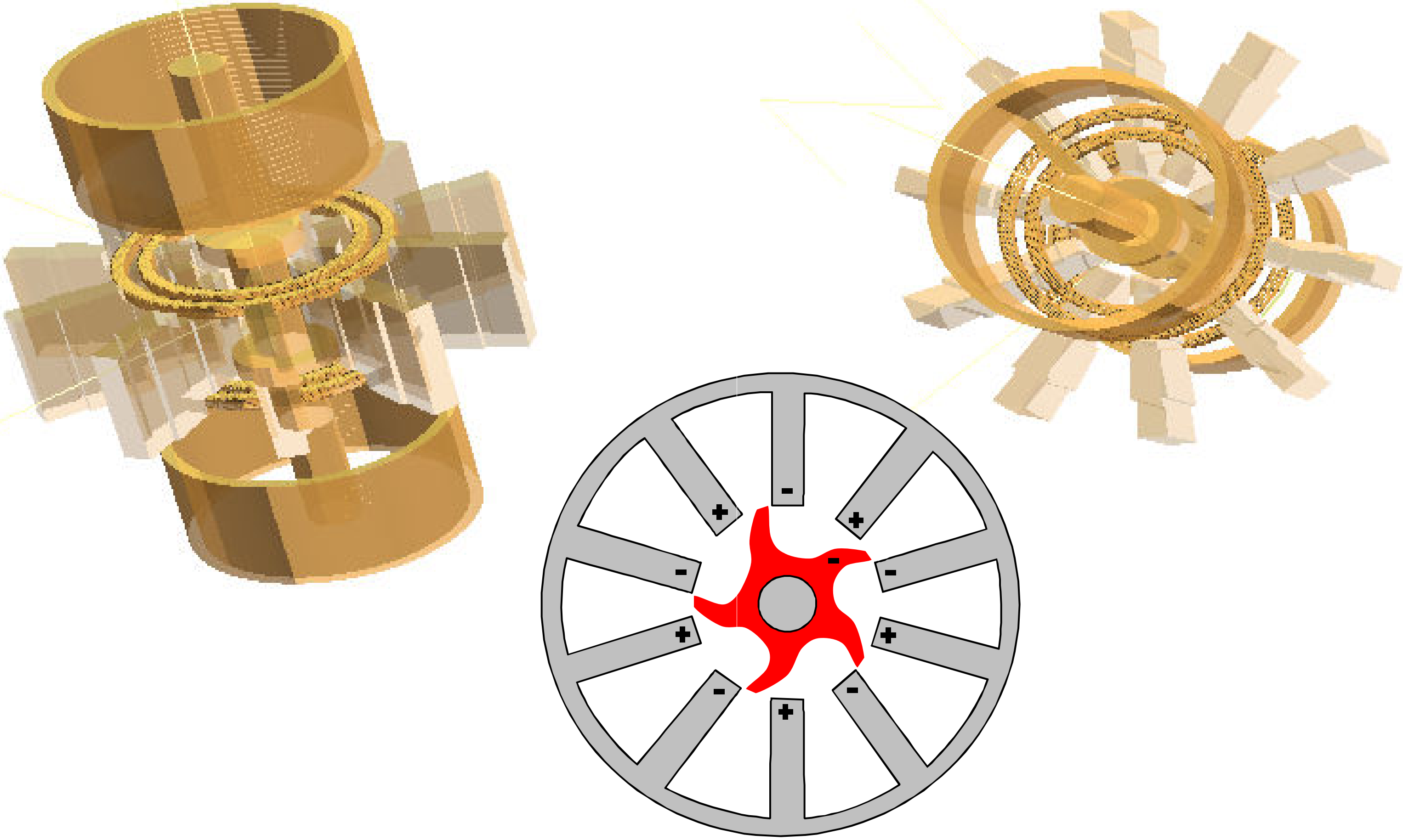
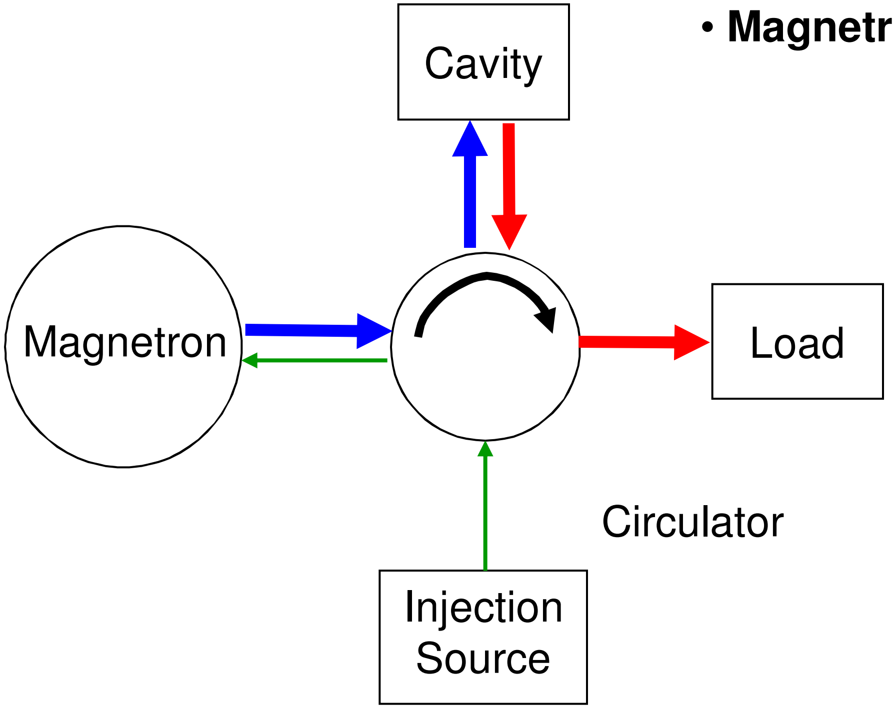
A magnetron solution for SPL?

Amos Dexter, Imran Tahir, Bob Rimmer and Richard Carter



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 (at 704 MHz)
- utilise lower d.c. voltage but higher current
- are easier to manufacture

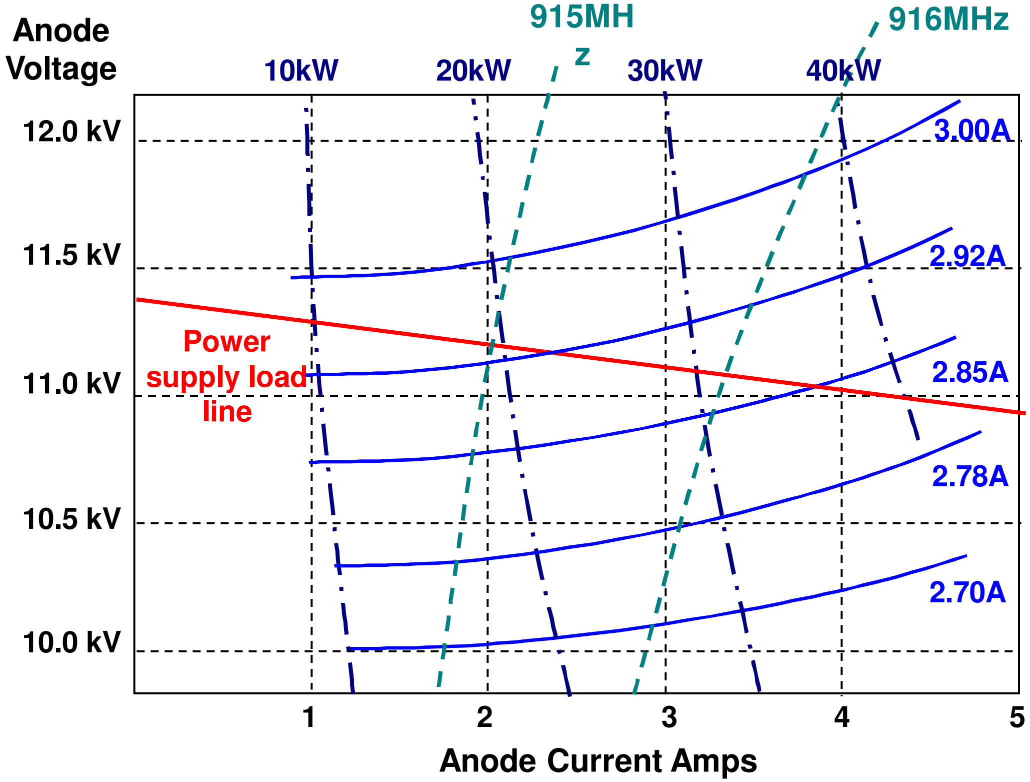
Consequently they are much cheaper to purchase and operate

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

Reflection Amplifier Controllability

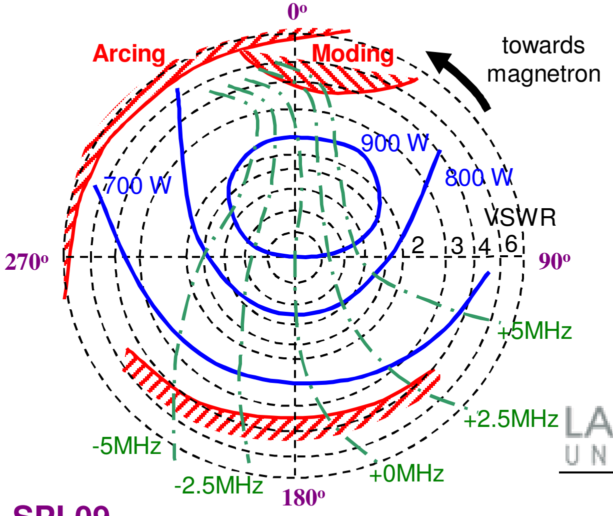
1. Phase of output follows the phase of the input signal
2. Phase shift through magnetron depends on difference between input frequency and the magnetrons natural frequency
3. Output power has minimal dependence on input signal power
4. Phase shift through magnetron depends on input signal power
5. There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



Magnetic field coil current

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)



SPL09

Magnetrons for Accelerators

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.

Courtesy of e2v

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

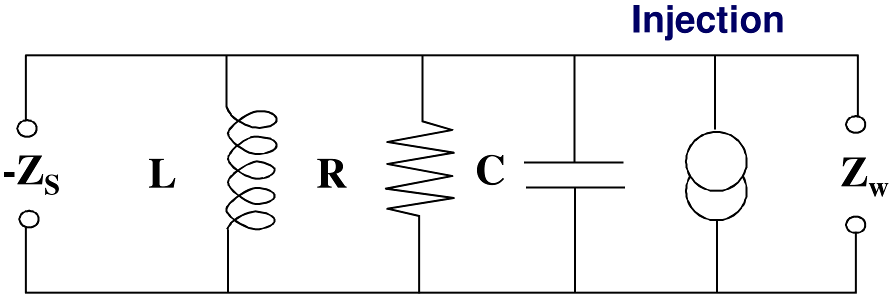
Adler's Equation for Injection Locking

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

Shien Chi Chen "Growth and frequency Pushing effects in Relativistic Magnetron Phase – Locking", IEEE Trans. on Plasma Science Vol. 18 No 3. June 1990.

The basic circuit model for the phased locked magnetron is the same as for a cavity

Negative impedance to represent magnetron spokes excitation of the anode. Includes static pushing effects.



Load impedance includes pulling effects.

$$\ddot{V} - \frac{\omega_o}{Q_w}\left(\frac{Z_w}{Z_s} - \frac{Z_w}{R} - 1\right)\dot{V} + \omega_o^2 V = -j\frac{\omega_o \omega_i}{Q_w} V_{inj} \exp\left(-j\omega_i t\right)$$

To get Adler's equation set $V(t) = A(t)\exp\{-j(\omega t + \psi(t))\}$

to give $$\frac{d\psi}{dt} = -\frac{V_{inj}}{V_{RF}}\frac{\omega_o}{2Q_L}\sin\psi + \omega_o - \omega_i$$

Solution of Adler’s Equation

$$\frac{d\psi}{dt} = -\frac{V_{inj}}{V_{RF}}\frac{\omega_o}{2Q_L}\sin\psi + \omega_o - \omega_i$$

Like $\frac{d\psi}{dt} = -A\psi + \text{const}$

for small ψ hence phase stabilises to a constant offset

ω_o	**magnetron ang. oscillation frequency without injection**
ω_{inj}	**injection angular frequency**
ψ	**phase shift between injection input and magnetron output**
$V_{inj/RF}$	**equivalent circuit voltage for injection signal / RF output**

Adler’s equation predicts that :-

if $\omega_o = \omega_i$ then $\psi \to 0$

if ω_o close to ω_i then $\psi \to$ a fixed value (i.e. when $\sin\psi < 1$ then locking occurs)

if ω_o far from ω_i then $\psi \to$ no locking unless V_{inj} is large

Steady state

$$\sin\psi = 2Q_L\sqrt{\frac{P_{RF}}{P_{inj}}}\;\frac{\omega_o - \omega_i}{\omega_o}$$

If the natural frequency of the magnetron is fluctuating then the phase ψ will be fluctuating.

High frequency phase jitter will be filtered by a superconducting the cavity

Advancing or retarding the injection signal allows low frequency jitter to be cancelled and the magnetron phase or the cavity phase to be maintained with respect to a reference signal.

Power Needed for Injection Locking

The minimum locking power is given when sin ψ = 1

$$P_{inj} = 4 P_{RF} Q_L^2 \left(\frac{\omega_i - \omega_o}{\omega_o} \right)^2$$

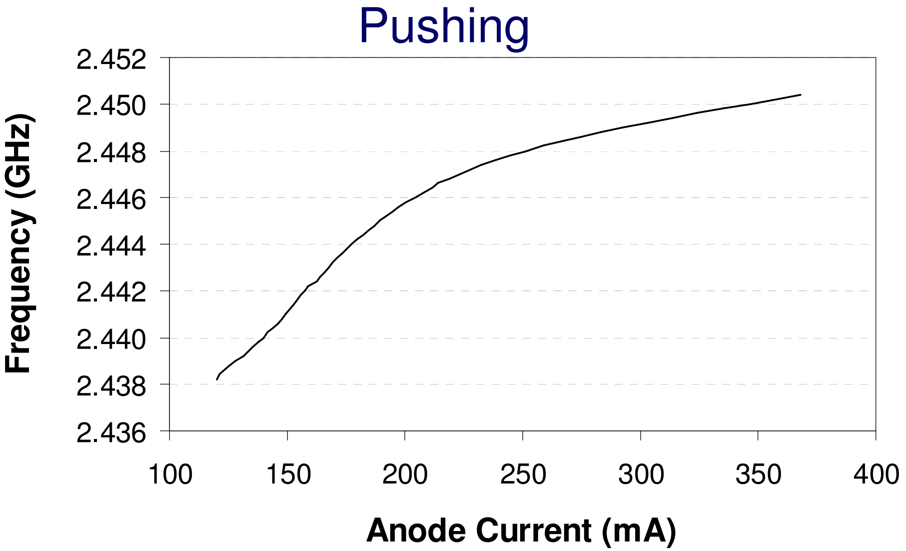
P_{RF} is output power
Q_L refers to the loaded magnetron.

For our 2.45 GHz cooker magnetron

($f_i - f_o$) due to ripple ~ 2 MHz
($f_i - f_o$) due to temperature fluctuation > 5 MHz

$$\frac{P_{lock}}{P_{output}} = 4Q^2 \left(\frac{f_i - f_o}{f_o} \right)^2 = 4 \times 100^2 \times \left(\frac{2.455 - 2.450}{2.450} \right)^2$$

$$\frac{P_{lock}}{P_{output}} = 0.166$$



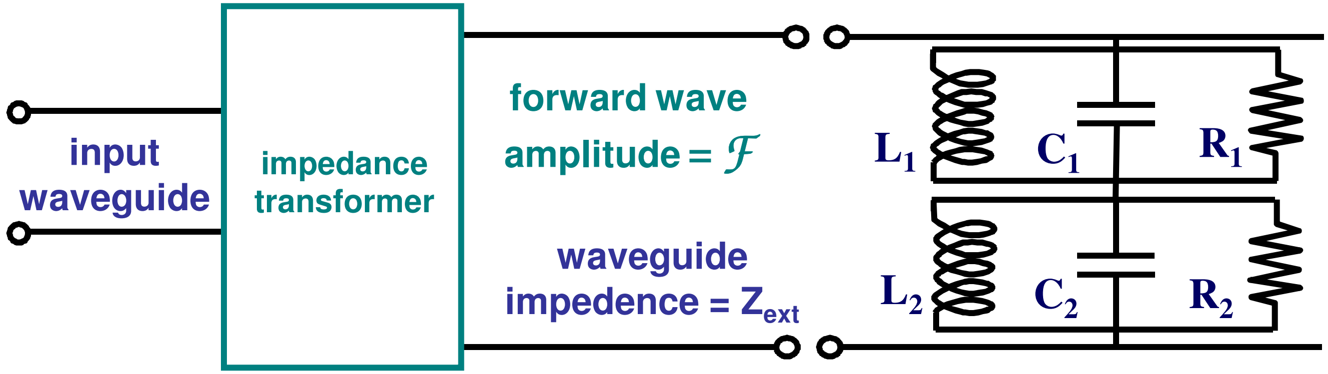
This is big hence must reduce $f_i - f_o$ (can do this dynamically using the pushing curve)

Time response ~ $$\frac{2Q_w}{\omega_o} \sqrt{\frac{P_{RF}}{P_{inj}}} \sim \frac{200}{2\pi \times 2.45 \times 10^9} \sqrt{\frac{1000}{1}}$$ **~ 400 ns ~ 1000 RF cycles**

sLHC

Amplifier Requirement to Drive S.C. Cavity

A full system model assists in understanding amplifier requirement


input waveguide

impedance transformer

forward wave amplitude = $\mathcal{F}$

waveguide impedence = Z_{ext}

equivalent electrical circuit for excitation of two cavity modes

$$\frac{1}{L_i}\int V_i dt + C_i \frac{dV_i}{dt} + \frac{V_i}{R_i} + \frac{1}{Z_{wg}}\sum_{j=1}^{N} V_j = \frac{2\mathcal{F}}{Z_{wg}}\exp(-j\omega t)$$

resulting differential equation for N modes (Numerically solve envelope equations)

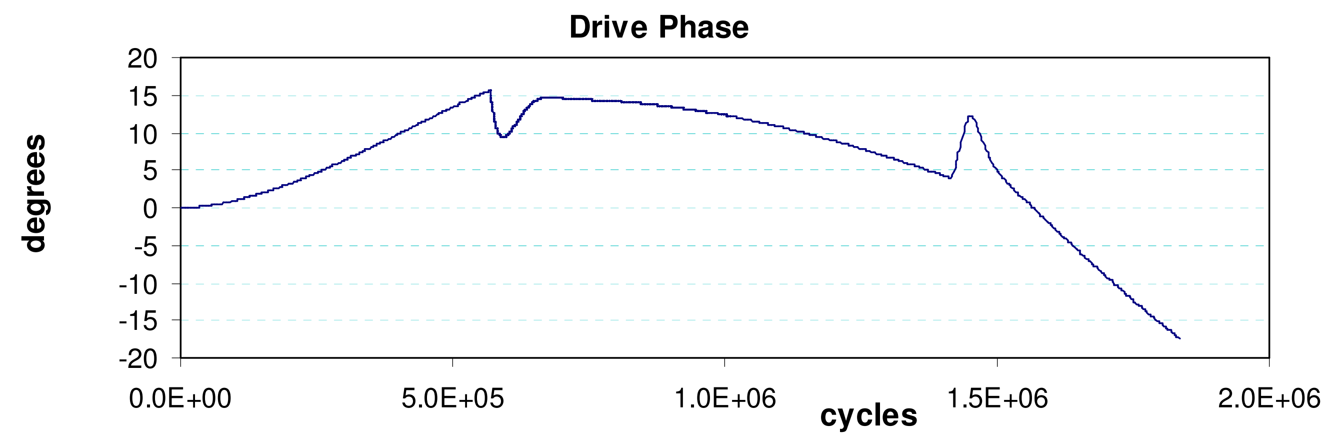
$$Q_i = \omega_i R_i C_i \qquad \omega_i = \frac{1}{\sqrt{L_i C_i}} \qquad \frac{Q_{ie}}{Q_i} = \frac{Z_{wgi}}{R_i}$$

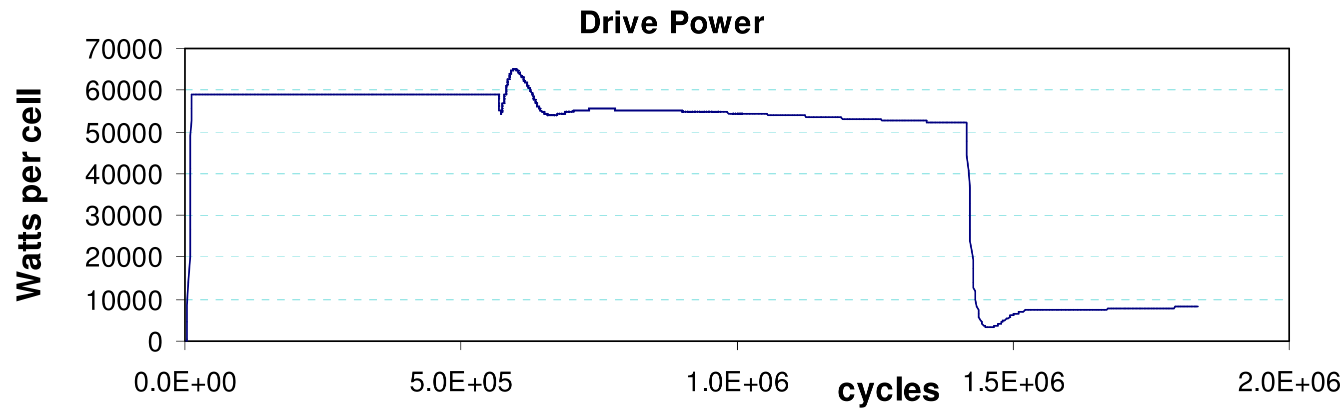
conversion from circuit parameters to cavity parameters

- Microphonics cause ω_i to vary with time
- Beamloading causes V to jump when a bunch passes through
- The amplitude and phase of $\mathcal{F}$ depend on the controller, the amplifier characteristics and the coupler temperature

Amplifier action for SPL cavity - case 1

- **Fill at almost full power**
- **PI control plus simple feed forward when pulse arrives**
- **Drive power and drive phase depends on cavity frequency offset caused by microphonics and Lorentz detuning**

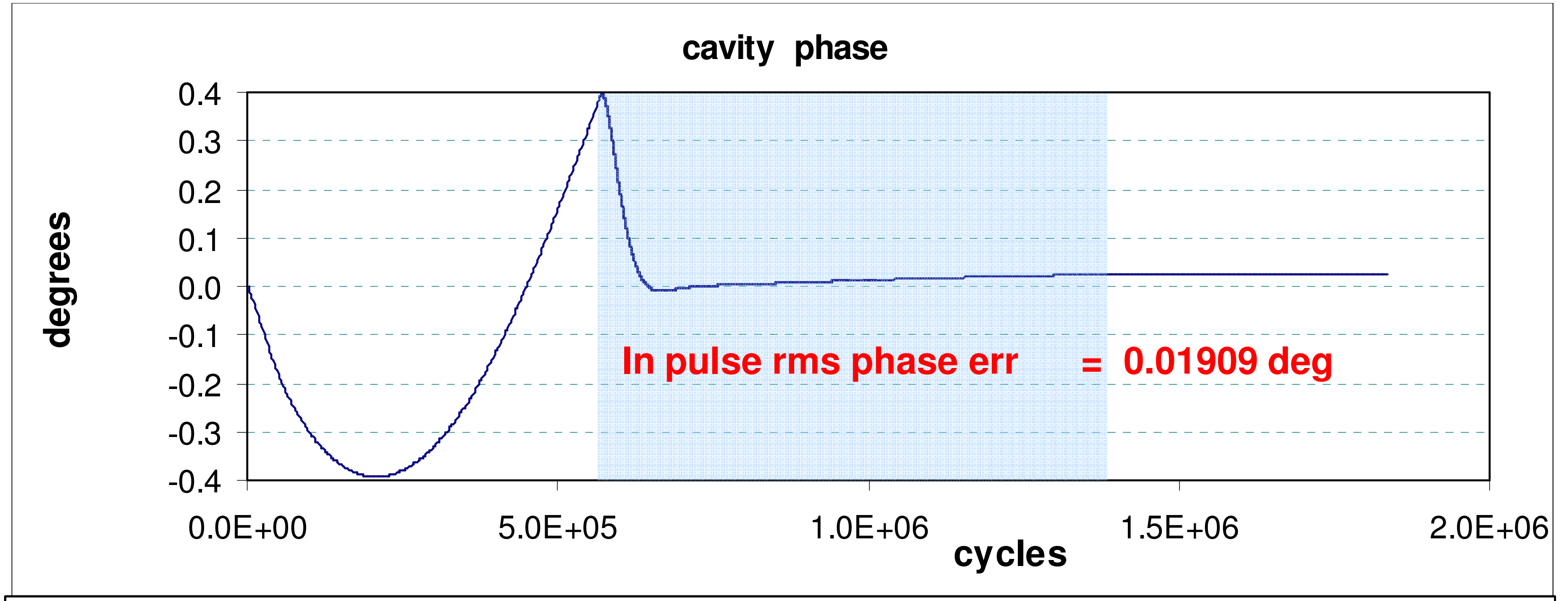

Drive Phase


Drive Power

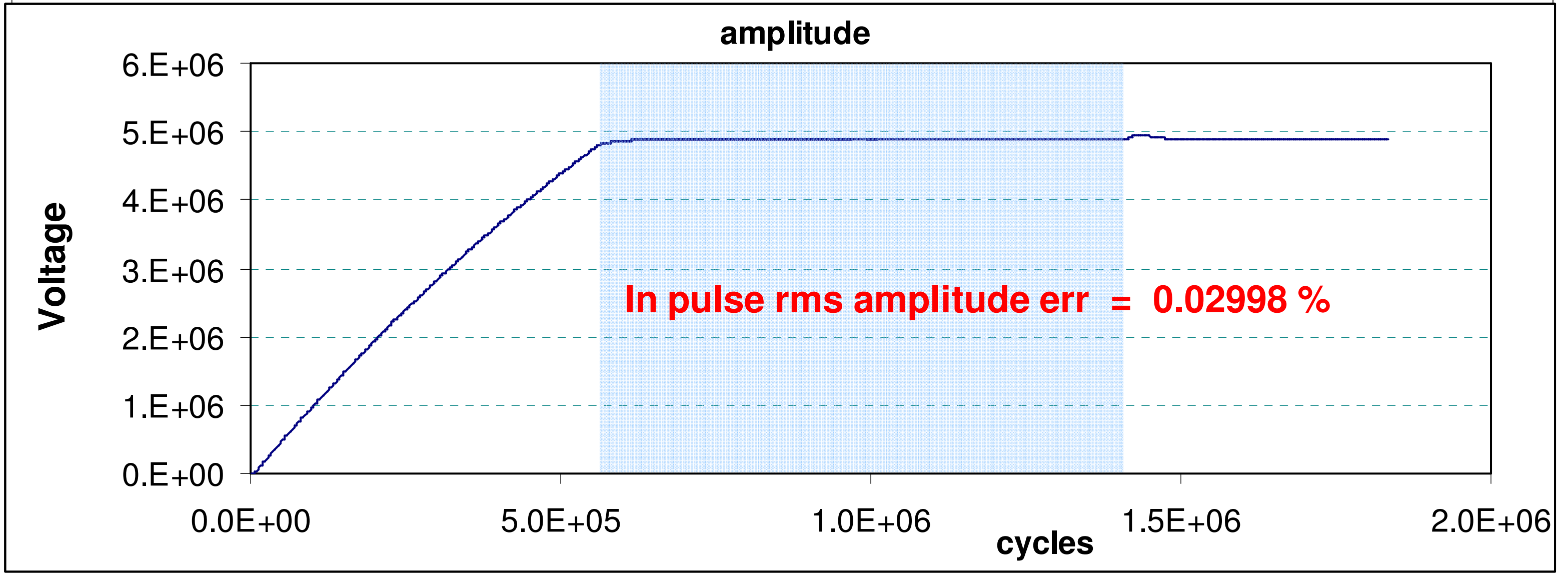
Plausible parameters

Drive frequency in GHz = 0.704 GHz
Centre cavity frequency in GHz = 0.704 GHz
Number of cavity modes included = 1
Cavity Q factor = 1.0 E+09
External Q factor = 4.0 E+06
Cavity R over Q = 100 ohms
Energy set point = 21.8 J
Amplitude set point = 4.8792 MV
Max Amplifier Power per cell = 59 kW
Max voltage set point (no beam) = 13.740 MV
Target fill time = 9.0E-04 s
Cycle number for beam arrival = 568000
Maximum bunch phase jitter = 0.000 deg
Bunch charge (ILC=3.2 nC) = 0.057 nC
RF cycles between bunches = 2.0
Bunch train length = 1.2 ms
Cavity frequency shift from microphonics = 60 Hz
Cavity vibration frequency = 200 Hz
Phase measurement error(degrees) = 0.000 deg
Fractional err in amplitude measurement = 0.0000
Time delay (latency) for control system = 1.0E-06 s
Control update interval = 1.0E-06 s
Gain constant for controller = 0.55
Beam arrival real feedforward term = 0.50E+10
Beam arrival imag feedforward term = 0.13E+10
Amplifier bandwidth = 1.0E+06
Measurement filter bandwidth = 5.0E+05
In pulse rms phase err = 0.01909 deg
In pulse rms amplitude err = 0.02998 %

Phase and amplitude control – case 1



In pulse rms phase err = 0.01909 deg

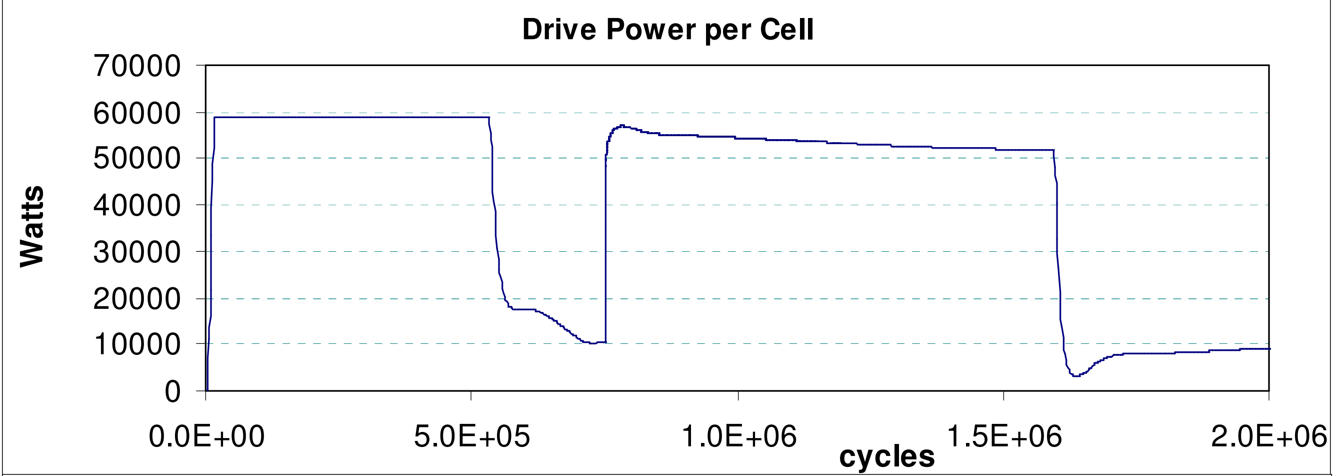


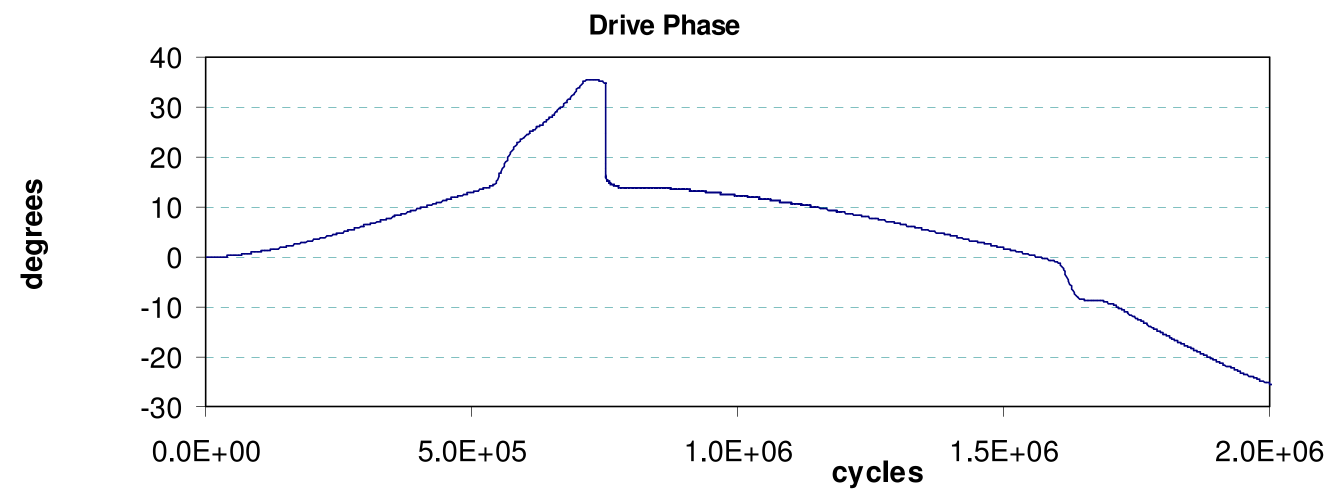
In pulse rms amplitude err = 0.02998 %

Filling at almost full power may give poor phase accuracy at start of bunch train

Amplifier action for SPL cavity - case 2

- **Reduce fill rate as cavity approaches set point, the control system can then fix the phase error.**
- **PI control plus simple feed forward when pulse arrives**





Plausible parameters

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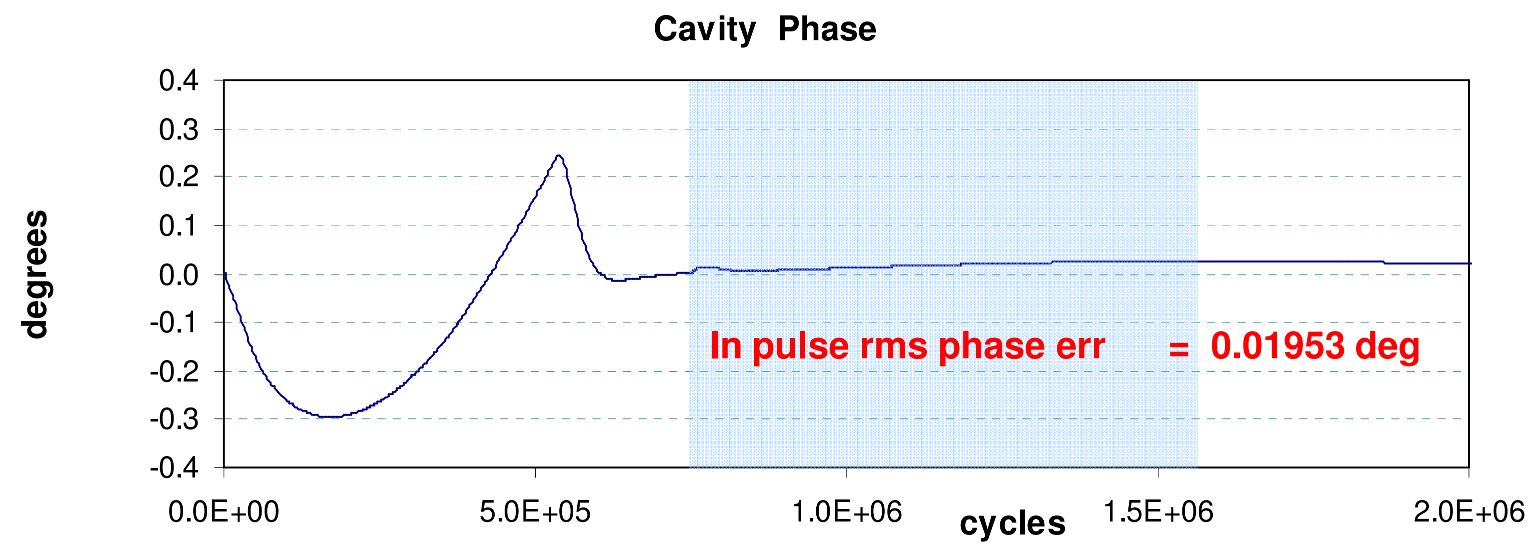
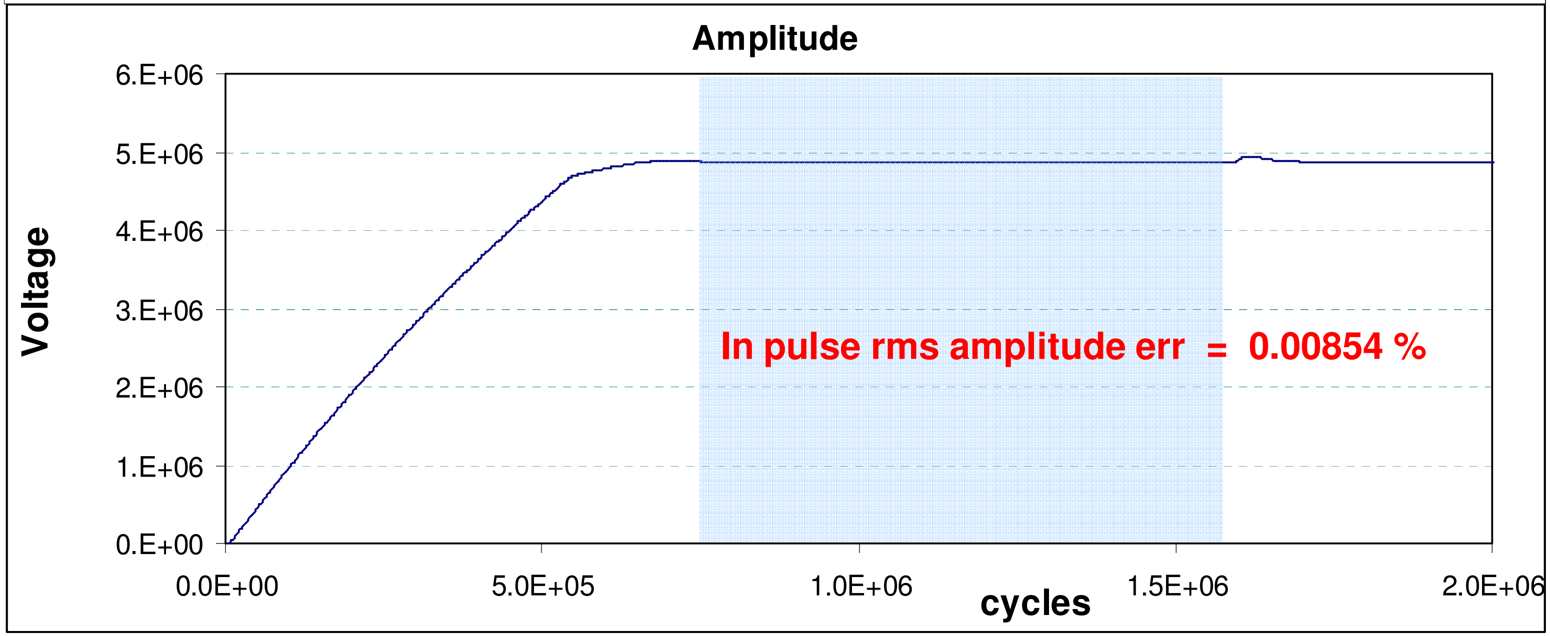
Centre cavity frequency in GHz = 0.704 GHz
Number of cavity modes included = 1
Cavity Q factor = 1.0 E+09
External Q factor = 4.0 E+06
Cavity R over Q = 100 ohms
Energy set point = 21.8 J
Amplitude set point = 4.8792 MV
Max Amplifier Power per cell = 59 kW
Max voltage set point (no beam) = 13.740 MV
Target fill time = 10.0E-04 s
Cycle number for beam arrival = 750000
Maximum bunch phase jitter = 0.000 deg
Bunch charge (ILC=3.2 nC) = 0.057 nC
RF cycles between bunches = 2.0
Bunch train length = 1.2 ms
Cavity frequency shift from microphonics = 60 Hz
Cavity vibration frequency = 200 Hz
Phase measurement error(degrees) = 0.000 deg
Fractional err in amplitude measurement = 0.0000
Time delay (latency) for control system = 1.0E-06 s
Control update interval = 1.0E-06 s
Gain constant for controller = 0.55
Beam arrival real feedforward term = 0.50E+10
Beam arrival imag feedforward term = 0.13E+10
Amplifier bandwidth = 1.0E+06
Measurement filter bandwidth = 5.0E+05
In pulse rms phase err = 0.01953 deg
In pulse rms amplitude err = 0.00854 %

Phase and amplitude control – case 2



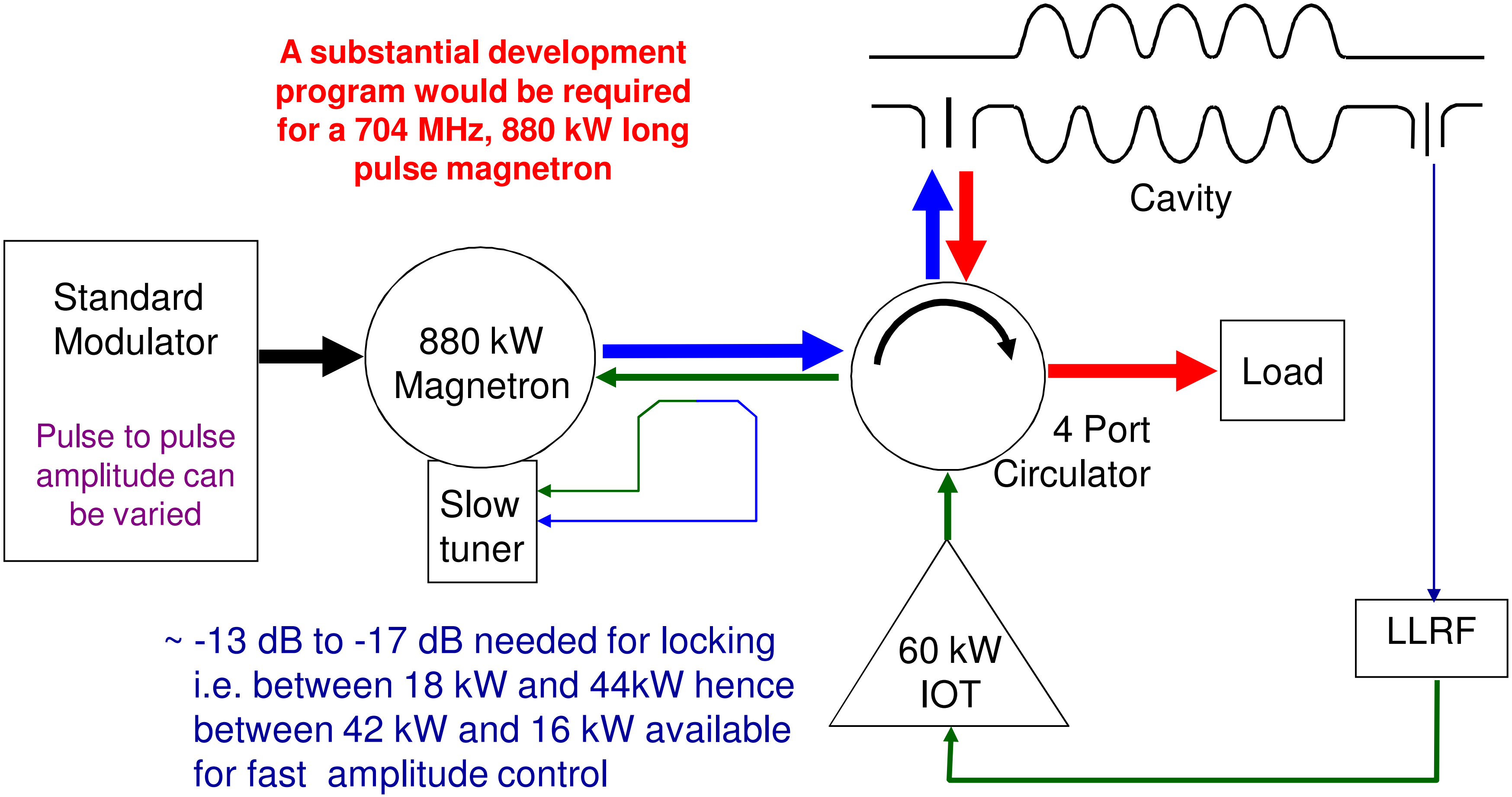


Phase correct at start of bunch train

Note that microphonics start with same phase as before but as the bunch arrives later the cavity frequency offset is greater and the resultant phase error is greater despite the better start.

Layout using one magnetron per cavity

Permits fast phase control but only slow, full range amplitude control



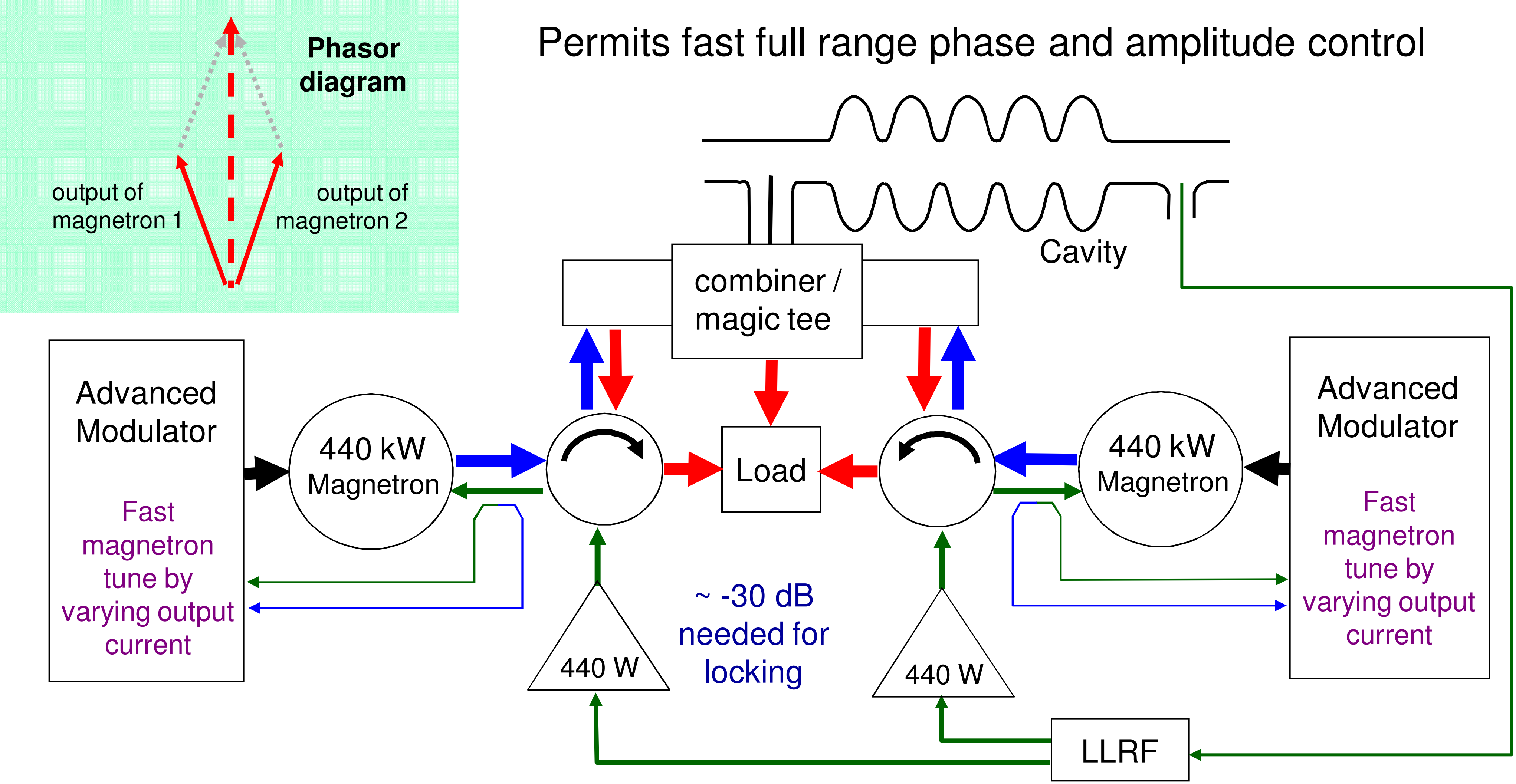
A substantial development program would be required for a 704 MHz, 880 kW long pulse magnetron

~ -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

sLHC

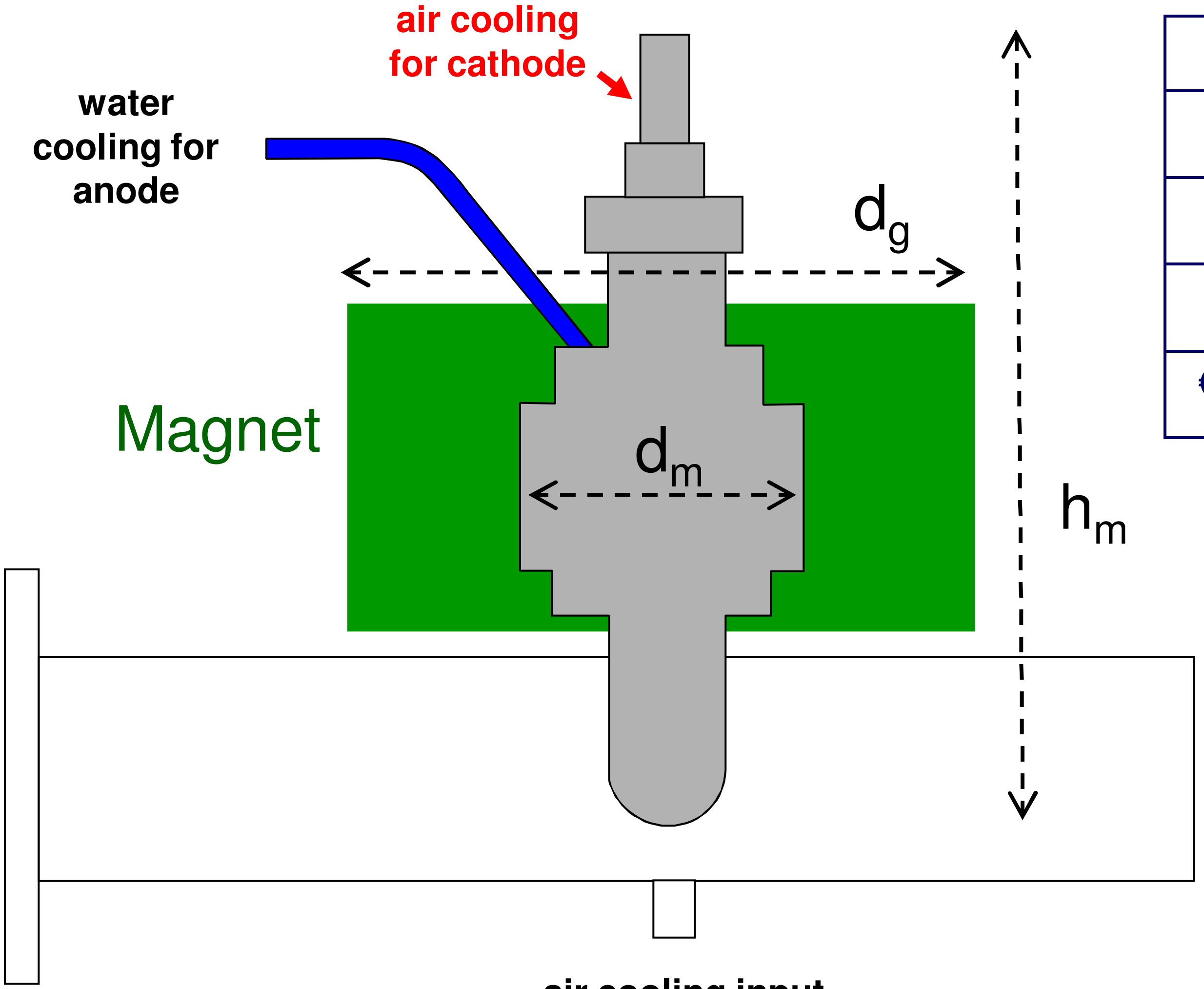
Layout using two magnetrons per cavity



Permits fast full range phase and amplitude control

440 kW Magnetron design is less demanding than 880 kW design reducing cost per kW, and increasing lifetime and reliability.

Magnetron Size



air cooling input for dome

	915 MHz	704 MHz
d_g	325 mm	~ 425 mm
d_m	125 mm	~ 165 mm
h_m	500 mm	~ 650 mm
€ tube	€ 8000	?

If magnetron design is similar to industrial design with similar tolerances and can be made on same production line then cost may not be much more

Cost Calculation 20 mA beam

20 mA beam		Two magnetrons per cavity	One Klystron per cavity	One Klystron four cavities	Notes
Tube Power	kW	220	440	1760	[1]
Duty cycle		0.05	0.05	0.05	[2]
Tube unit cost	k£	8	140 ?	260	[3]
Magnets, supplies and heater	k£	4 ?	20 ?	40 ?	
number of tubes		484	242	62	[4]
Tube total cost	**k£**	**5,808** ?	**38,720** ?	**18,600**	
Circulator unit cost	k£	9 ?	16 ?	30 ?	
Circulator cost	k£	4,356	3,872	1,860	[5]
HP phase shifter unit cost	k£	0	0	10 ?	[6]
Total phase shifter cost	k£	0	0	2,420	
Power of drive amplifier	W	300	30	120	[7]
Drive amplifier unit cost	k£	3.00 ?	0.60 ?	1.20 ?	
Number of drive amplifiers		484	242	62	[8]
Drive amplifier cost	k£	1,452	145	74	
Tube + drive + circulator cost	**k£**	**11,616**	**42,737**	**22,954**	
Modulator unit cost	k£	50 ?	100 ?	400 ?	[9]
Total modulator cost (Guess!)	**k£**	**24,200** ?	**24,200** ?	**24,800** ?	[10]
Tube life	yrs	2 ?	20 ?	10 ?	[11]
Annual tube replacement cost		2904	1936	1860	[12]
Efficency		0.88 ?	0.67 ?	0.67 ?	
Intalled RF power	kW	106480	106480	109120	
Power consumption	kW	6050	7946	8143	
Hours per year		4800	4800	4800	[13]
kWh cost	k£	0.00005	0.00005	0.00005	
Annual electricity cost	k£	1,452	1,907	1,954	
Cost after installation	**k£**	**35,816**	**66,937**	**47,754**	
Cost after 10 years	k£	79,376	105,368	85,898	
Status		[14]	[15]	[16]	

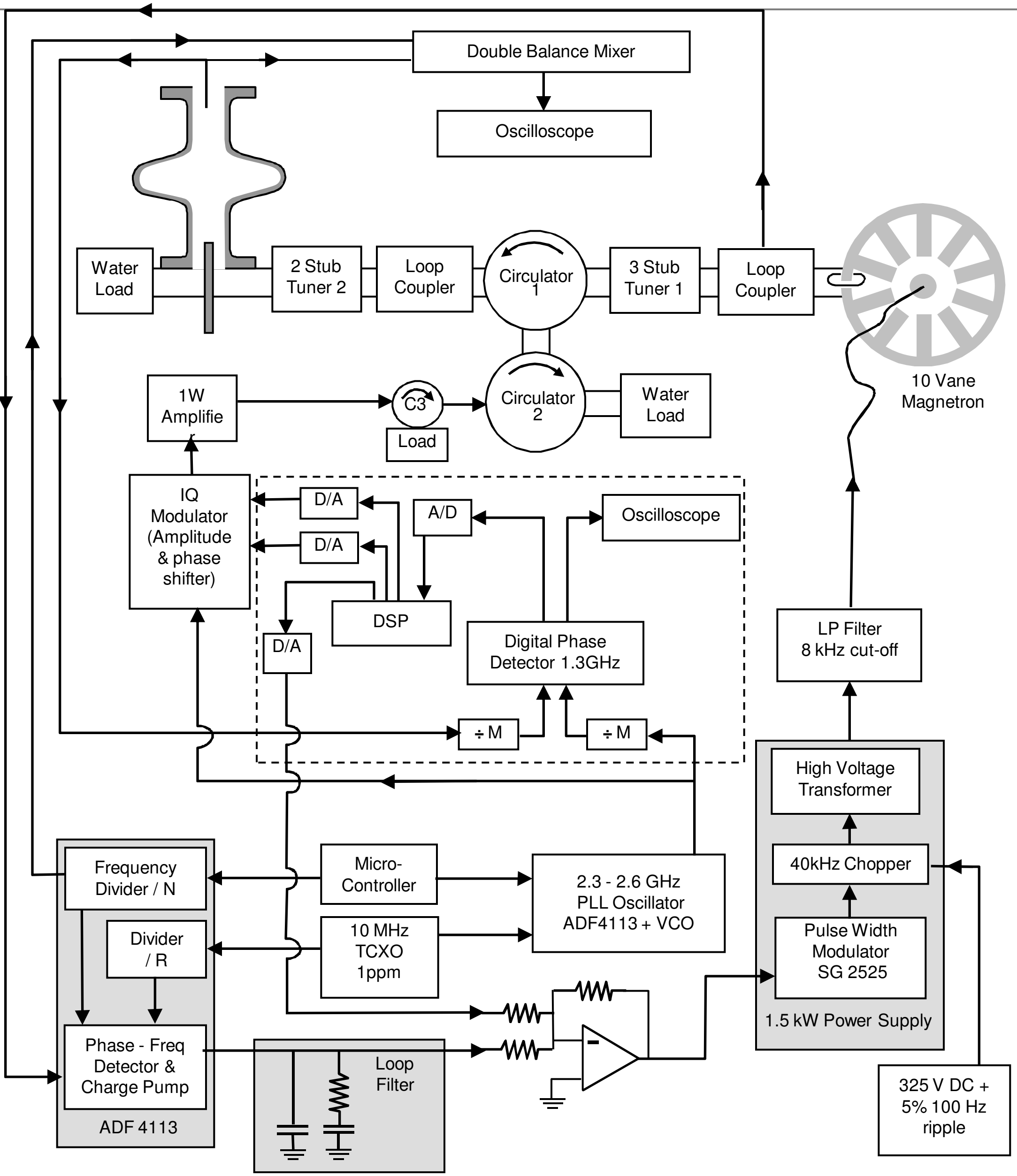
Notes for cost calculation

[1] Amplitude control needs two magnetrons with phase difference
[2] 50 Hz operation 1 ms pulse
[4] beta 0.92 cavities =200, beta 0.65 cavities =42, use same power source for all
[5] One circulator per tube - magnetron needs 4 port device
[6] One High Power Phase Shifter per cavity
[7] Use -28.5 dB magnetron drive and -42 dB Klystron drive
[8] One per tube
[9] One modulator per tube (Magnetron ~ 8 amps at 32 kV)
[10] Flat cost per kW assumed but magnetron uses half voltage hence maybe cheaper
[11] The 440 kW Klystron is assumed to be underated hence the good life
[12] Magnetron refurbishment would save much of this cost
[13] 200 days
[14] Unproven
[15] Available
[16] Needs development of high power phase shifter for 50Hz operation

Cost Calculation for 40 mA beam

40 mA beam		Two magnetrons per cavity	One Klystron per cavity	One Klystron four cavities
Tube Power	kW	440	880	3250
Duty cycle		0.05	0.05	0.05
Tube unit cost	k£	16	280 ?	520
Magnets, supplies and heater	k£	4 ?	20 ?	40 ?
number of tubes		484	242	62
Tube total cost	**k£**	**9,680** ?	**72,600** ?	**34,720**
Circulator unit cost	k£	14 ?	24 ?	45 ?
Circulator cost	k£	6,776	5,808	2,790
HP phase shifter unit cost	k£	0	0	30 ?
Total phase shifter cost	k£	0	0	7,260
Power of drive amplifier	W	600	60	240
Drive amplifier unit cost	k£	3.00 ?	0.60 ?	1.20 ?
Number of drive amplifiers		484	242	62
Drive amplifier cost	k£	1,452	145	74
Tube + drive + circulator cost	**k£**	**17,908**	**78,553**	**44,844**
Modulator unit cost	k£	100 ?	200 ?	800 ?
Total modulator cost (Guess!)	**k£**	**48,400** ?	**48,400** ?	**49,600** ?
Tube life	yrs	2 ?	20 ?	10 ?
Annual tube replacement cost		4840	3630	3472
Efficency		0.88 ?	0.67 ?	0.67 ?
Intalled RF power	kW	212960	212960	201500
Power consumption	kW	12100	15893	15037
Hours per year		4800	4800	4800
kWh cost	k£	0.00005	0.00005	0.00005
Annual electricity cost	k£	2,904	3,814	3,609
Cost after installation	**k£**	**66,308**	**126,953**	**94,444**
Cost after 10 years	k£	143,748	201,395	165,254
Status		[14]	[15]	[16]

Experiments at Lancaster



Double Balance Mixer

Oscilloscope

Water Load

2 Stub Tuner 2

Loop Coupler

Circulator 1

3 Stub Tuner 1

Loop Coupler

10 Vane Magnetron

1W Amplifie

C3

Load

Circulator 2

Water Load

IQ Modulator (Amplitude & phase shifter)

D/A

D/A

A/D

Oscilloscope

DSP

D/A

Digital Phase Detector 1.3GHz

÷M

÷M

LP Filter 8 kHz cut-off

High Voltage Transformer

40kHz Chopper

Pulse Width Modulator SG 2525

1.5 kW Power Supply

Frequency Divider / N

Divider / R

Phase - Freq Detector & Charge Pump

ADF 4113

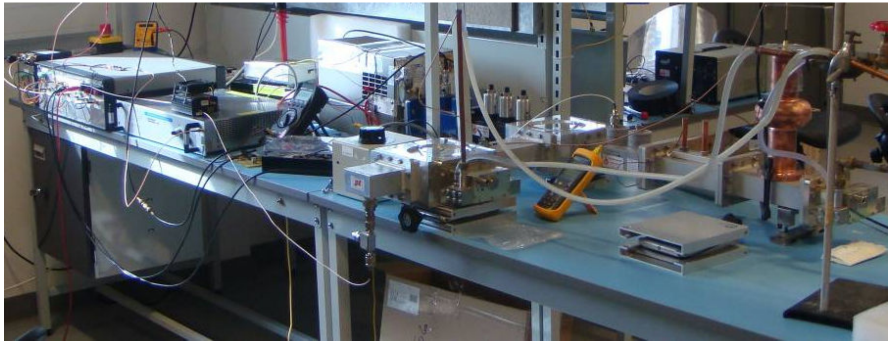
Micro-Controller

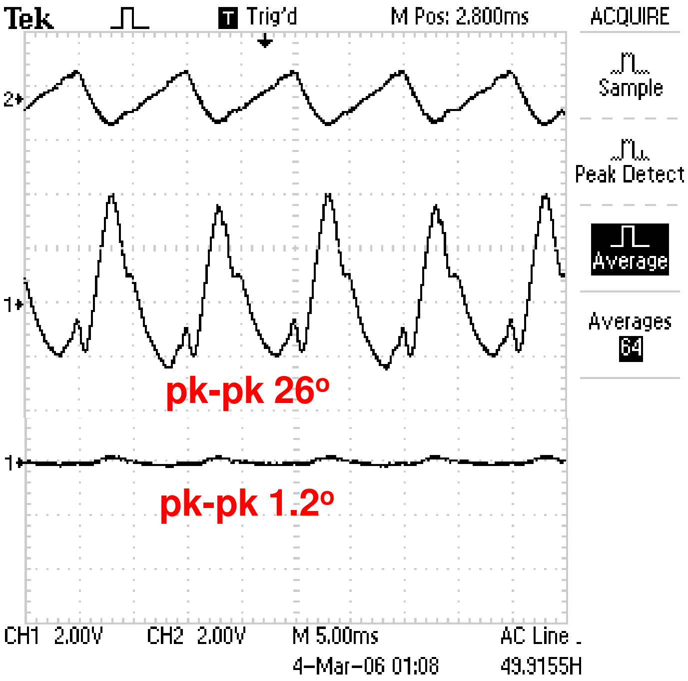
10 MHz TCXO 1ppm

2.3 - 2.6 GHz PLL Oscillator ADF4113 + VCO

Loop Filter

325 V DC + 5% 100 Hz ripple





Power supply ripple

Magnetron phase no LLRF

pk-pk 26°

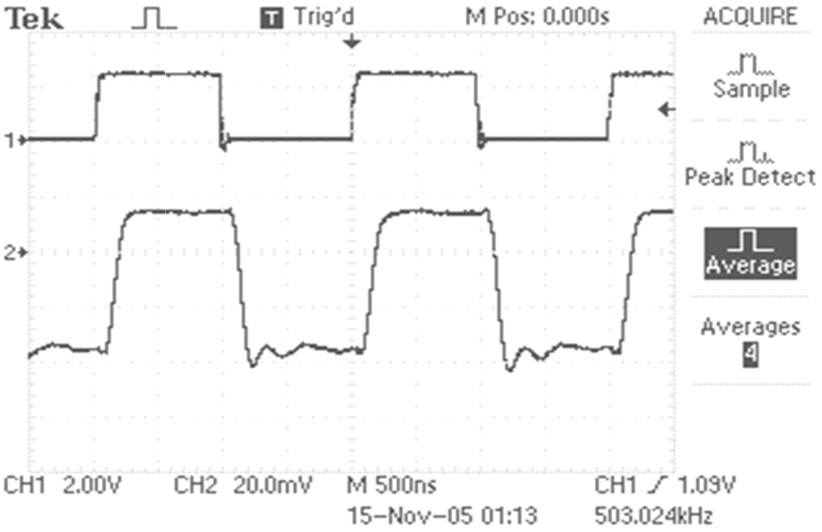
Magnetron phase with LLRF

pk-pk 1.2°

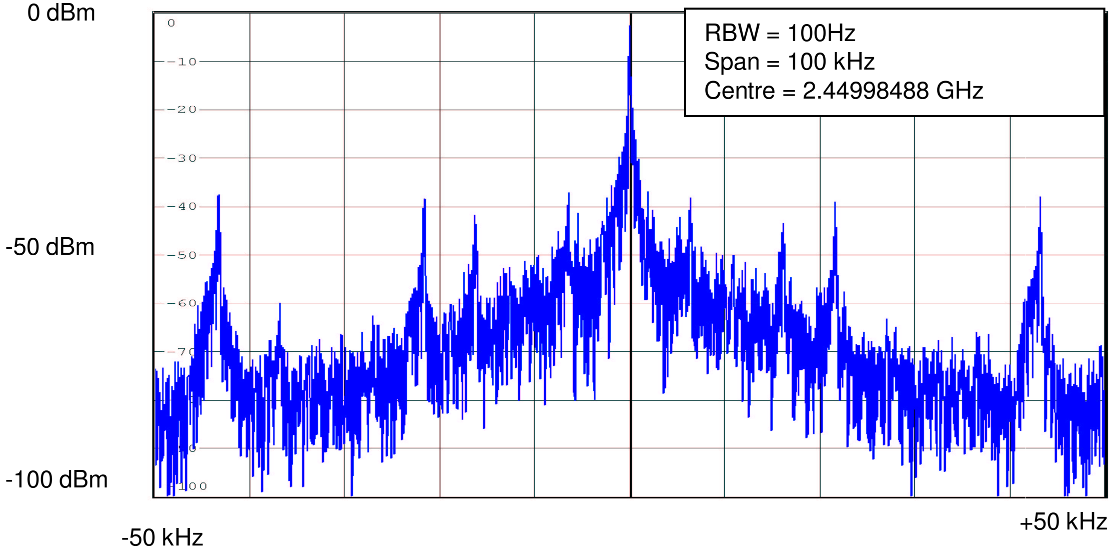
Experiments at Lancaster

Tahir I., **Dexter A.C** and Carter R.G. “Noise Performance of Frequency and Phase Locked CW Magnetrons operated as current controlled oscillators”, IEEE Trans. Elec. Dev, vol 52, no 9, 2005, pp2096-2130

Tahir I., **Dexter A.C** and Carter R.G., “Frequency and Phase Modulation Performance on an Injection-Locked CW Magnetron”, IEEE Trans. Elec. Dev, vol. 53, no 7, 2006, pp1721-1729



Phase shift keying the magnetron



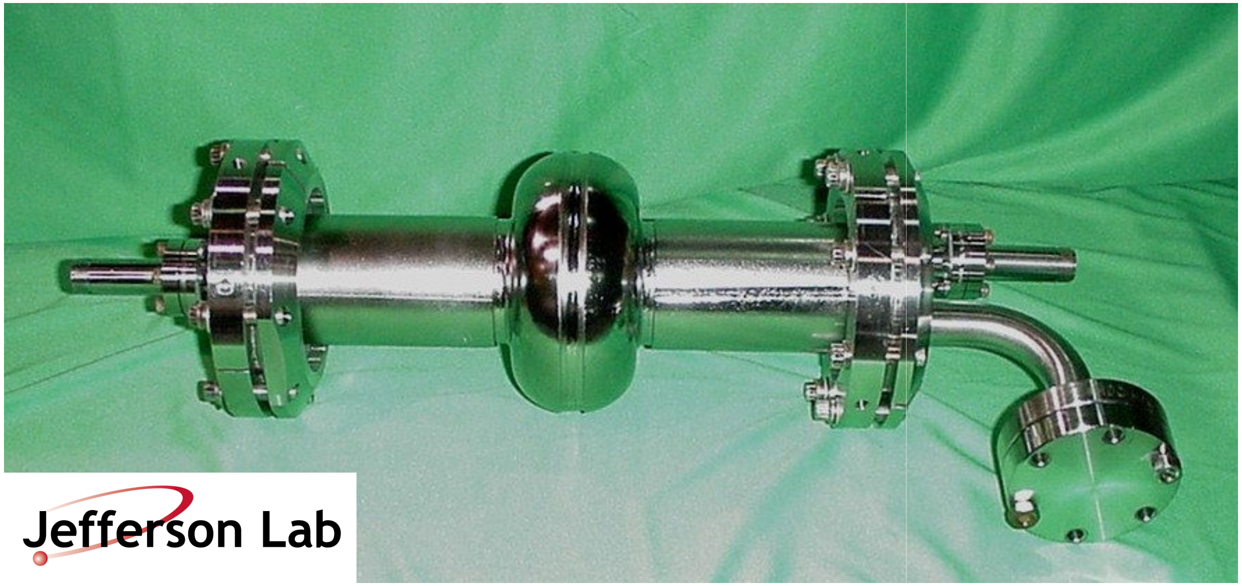
RBW = 100Hz
Span = 100 kHz
Centre = 2.44998488 GHz

Locked spectral output

Lancaster has successfully demonstrated the injection locking of a cooker magnetron with as little as -40 dB injection power by fine control the anode current to compensate shifts in the natural frequency of the magnetron.

Way Forward

- Commission the development of a 704MHz Magnetron (440kW)
- Procure standard modulator
- Set up test station with IOT as drive amplifier
- Understand locking characteristics of new magnetron
- Commission advanced modulator with in-pulse current control
- Establish minimum locking power
- Establish two magnetron test stand
- Develop LLRF for simultaneous phase and amplitude control



Demonstration of CW 2.45 GHz magnetron driving a specially manufactured superconducting cavity at JLab due later this month should stimulate more interest.