

PHASE LOCKED MAGNETRONS FOR ACCELERATORS

Amos Dexter

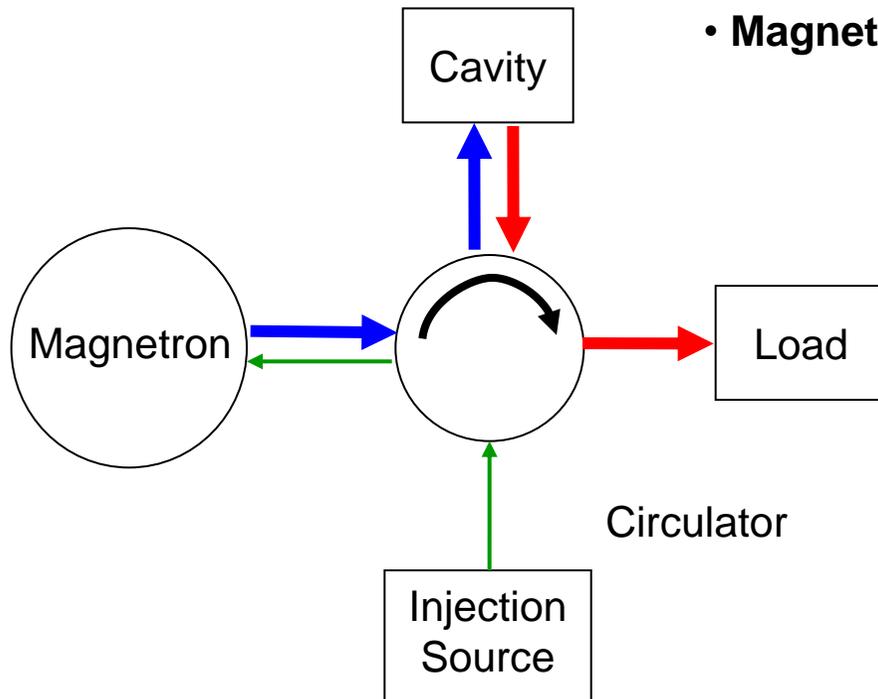
a.dexter@lancaster.ac.uk

Collaboration on SCRF demonstration

Lancaster Imran Tahir, Richard Carter, Graeme Burt

Jlab Haipeng Wang, Robert Rimmer, Kirk Davis

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



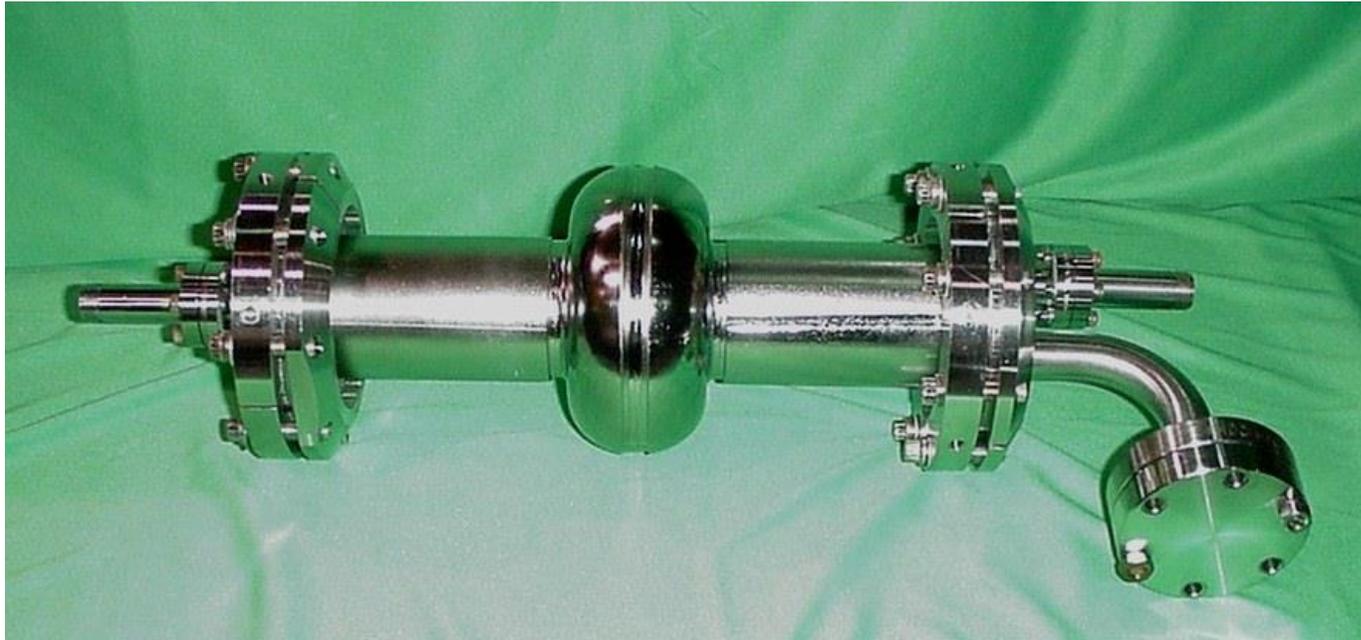
Compared to Klystrons, in general Magnetrons

- are smaller
- can be 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



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.

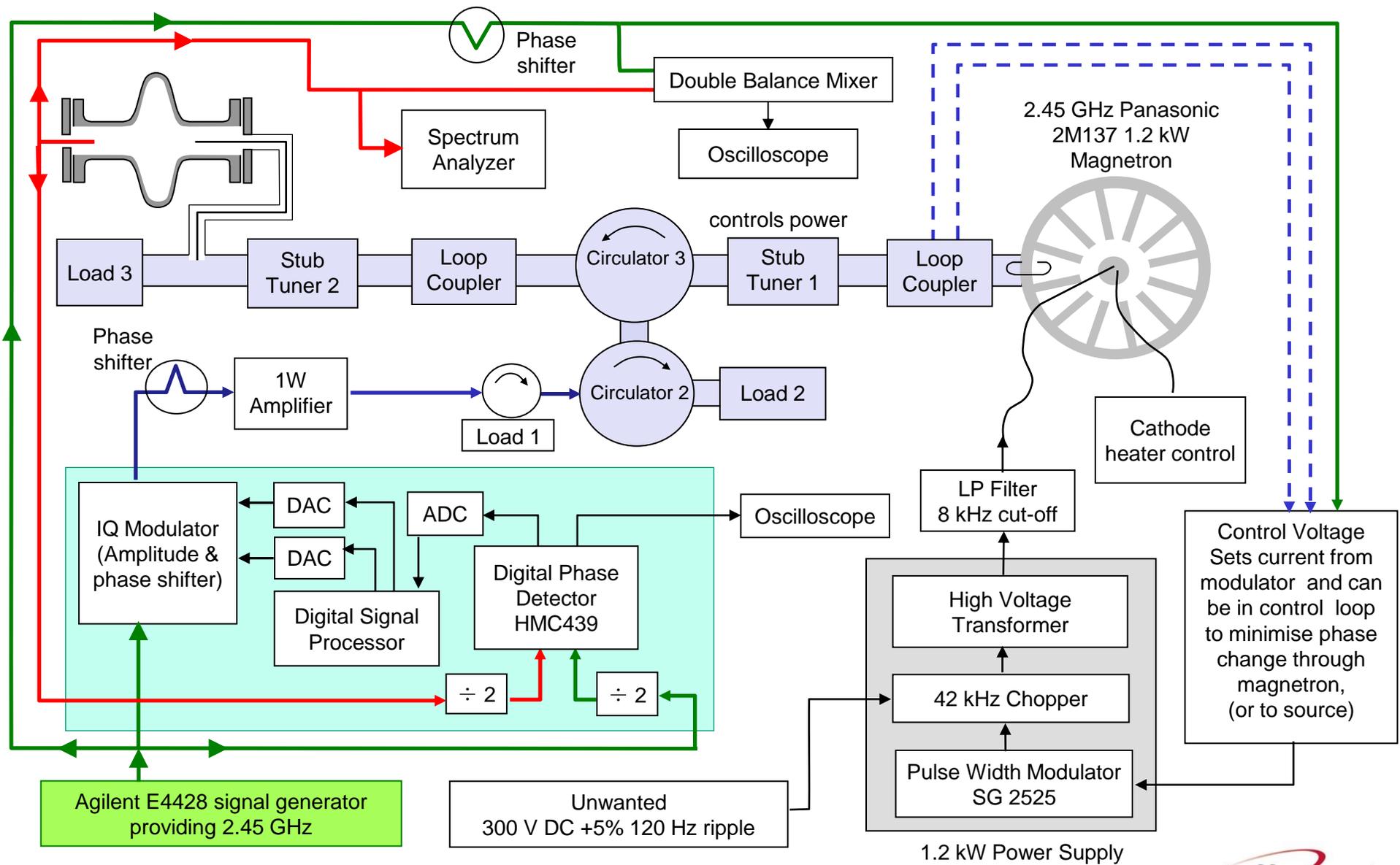
First demonstration and performance of an injection locked continuous wave magnetron to phase control a superconducting cavity

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.

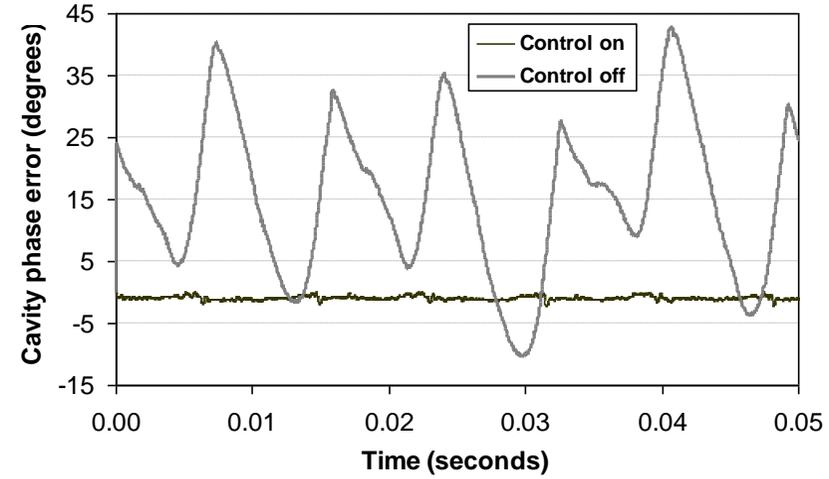
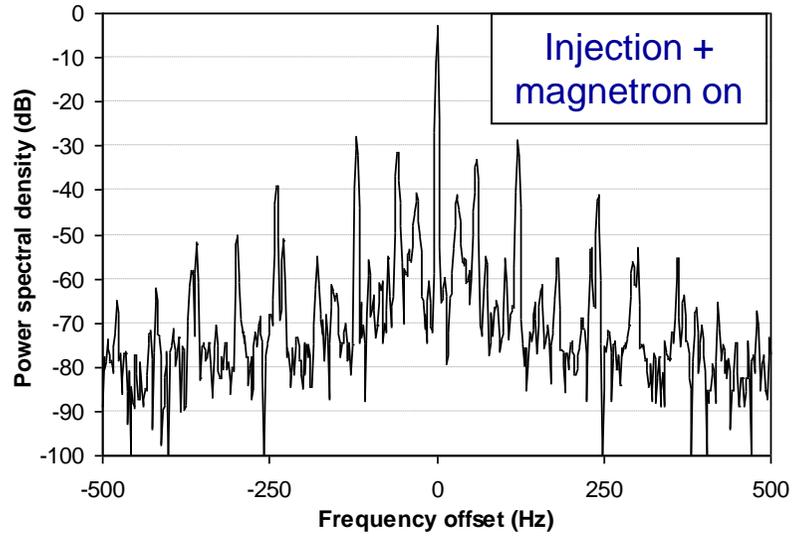
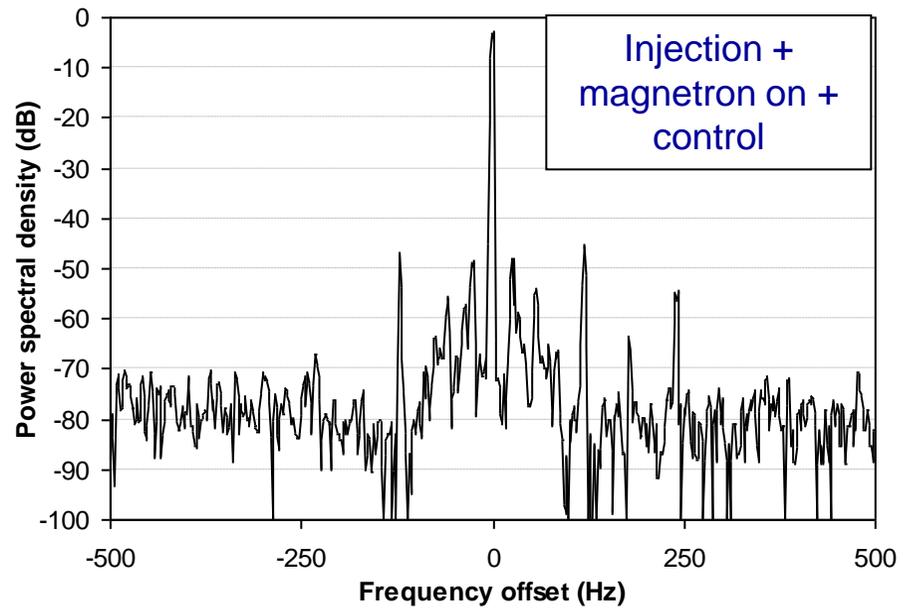
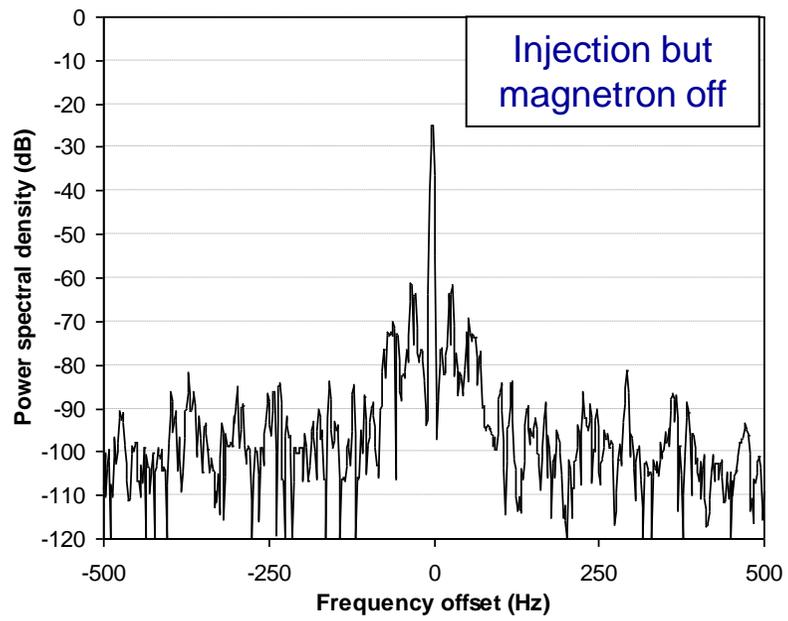
<http://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.14.032001>

Circuit for Phased Locked Operation

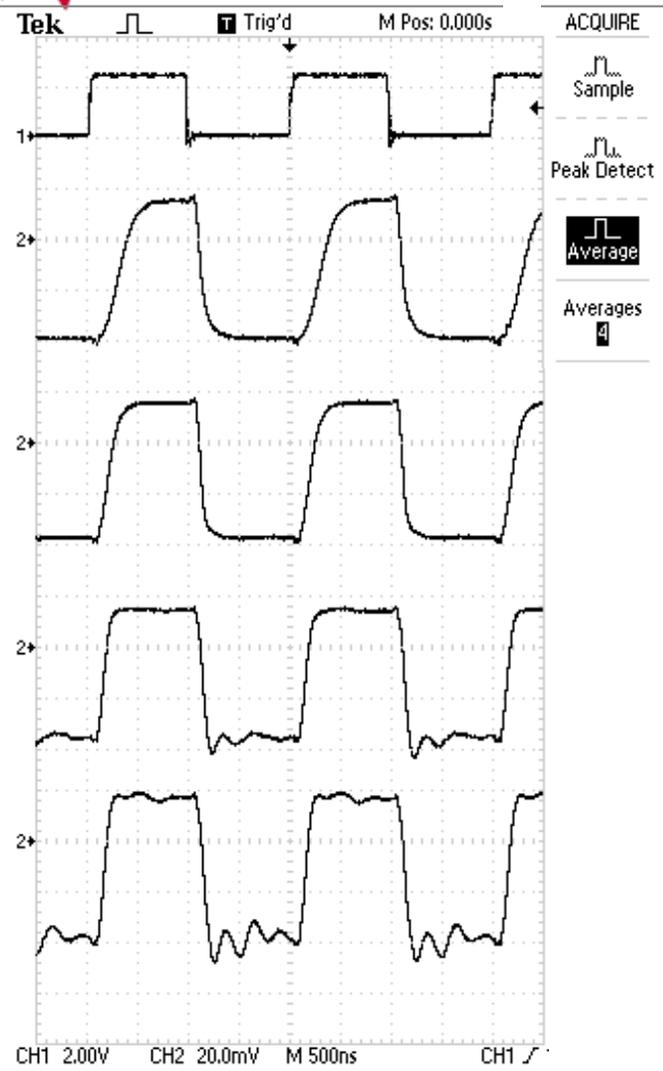




Phase Control Performance



Response as Function of Heater Power



Matched.



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

← Input wave

8 W heater

15 W heater

36 W heater

43 W heater



Amplifier Selection

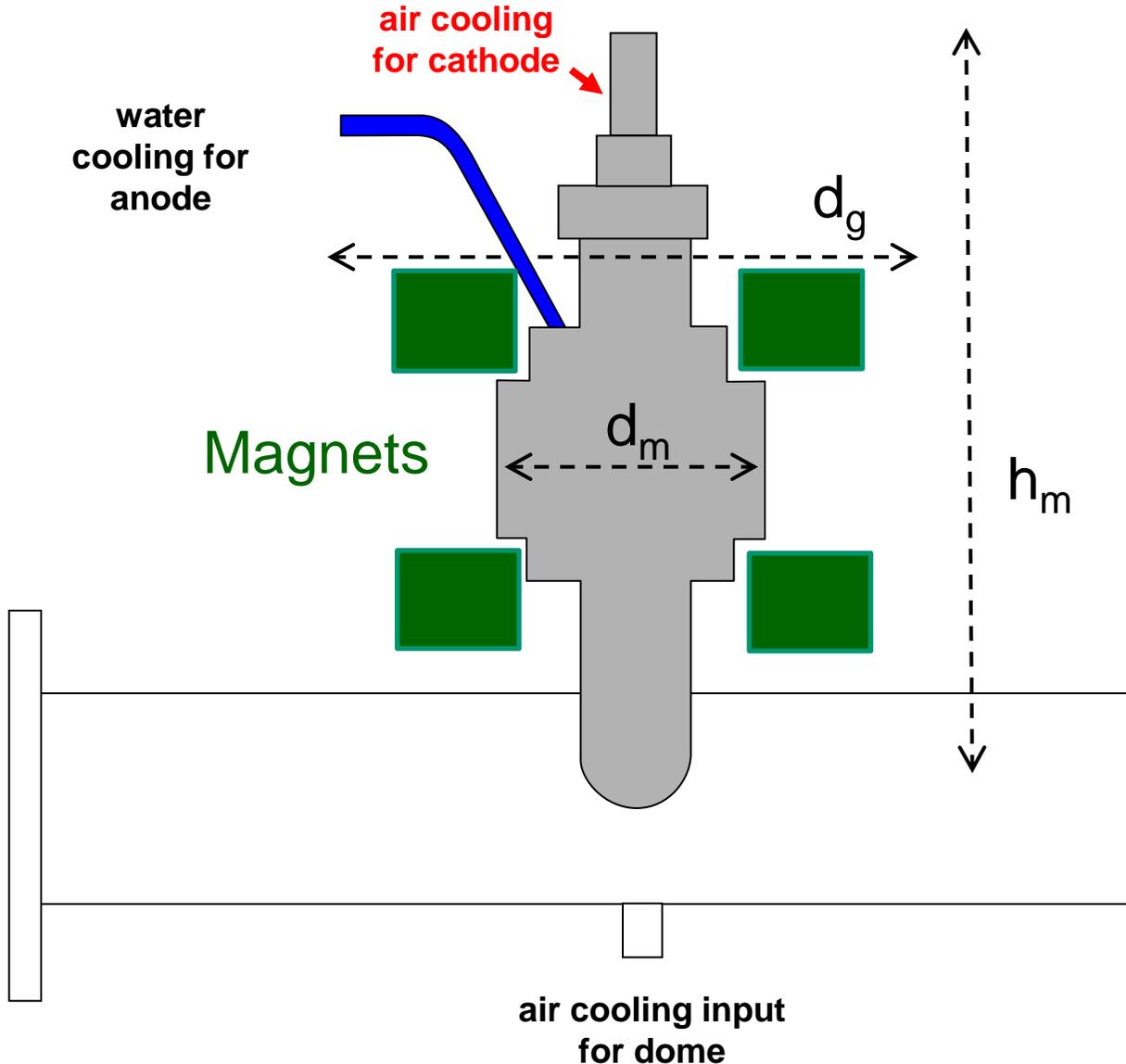
	Magnetron	Klystron
Peak Power	Lower	High
Average power	Lower	High
Gain	Lower	High
Tuneable range	Large	Small
Instantaneous bandwidth	Smaller	Small
Noise	Higher	Lower
Best Efficiency L band	~ 90%	ILC ~ 69%
Best Efficiency X band	~ 50%	XL5 = 40%
Pushing figure	Significant	Significant
Pulling figure	Significant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

You would not use a magnetron if capital and running costs are not an issue.

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.

Magnetron Size



	704 MHz
d_g	~ 360 mm
d_m	~ 165 mm
h_m	~ 650 mm
cost	£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

FERMILAB-PUB-13-315-AD-TD

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

Grigory Kazakevich*, Rolland Johnson, Gene Flanagan, Frank Marhauser,
Muons, Inc., Batavia, 60510 IL, USA

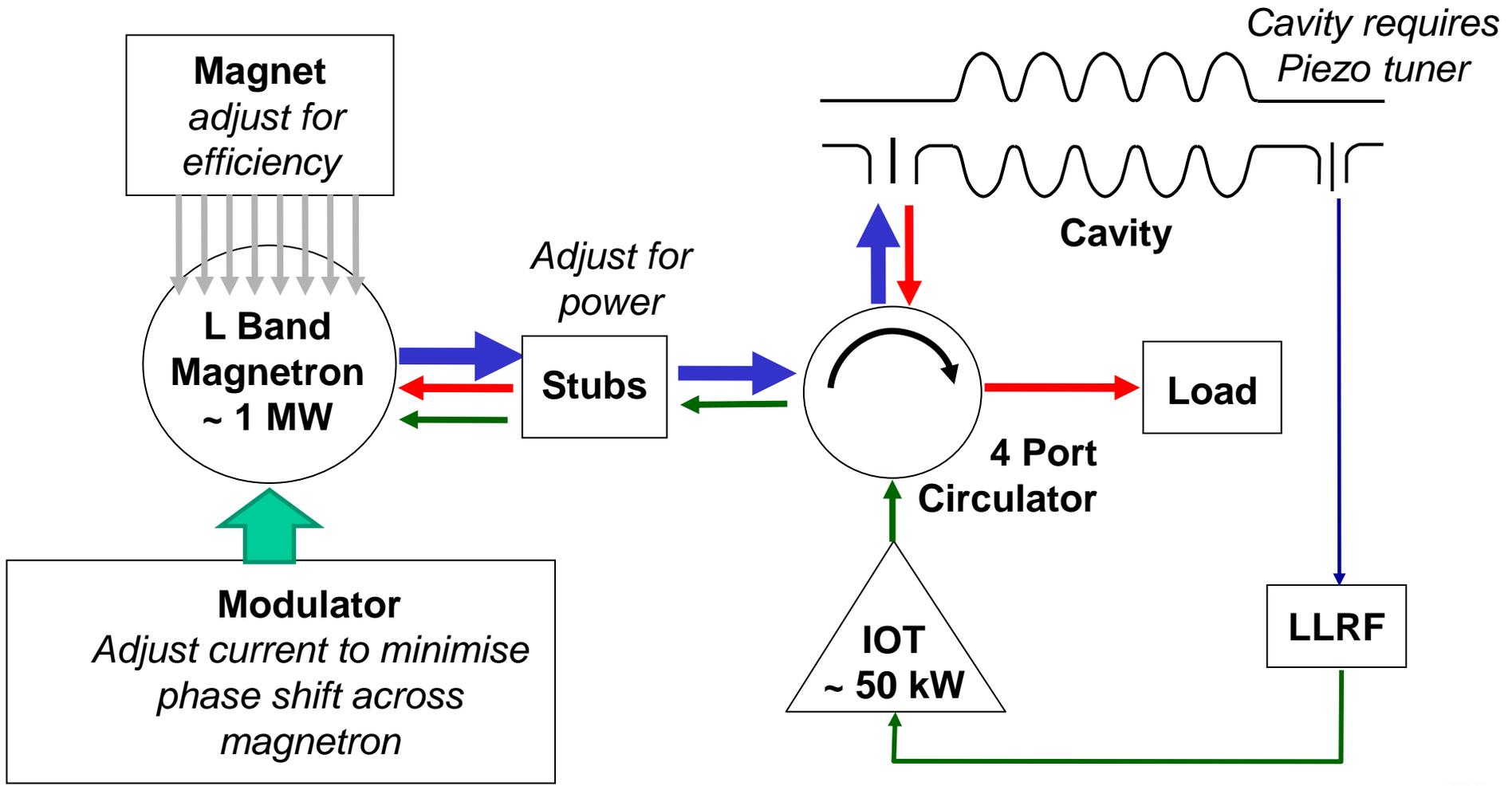
Vyacheslav Yakovlev, Brian Chase, Valeri Lebedev, Sergei Nagaitsev, Ralph Pasquinelli, Nikolay Solyak, Kenneth Quinn, and Daniel Wolff,
Fermilab, Batavia, 60510 IL, USA

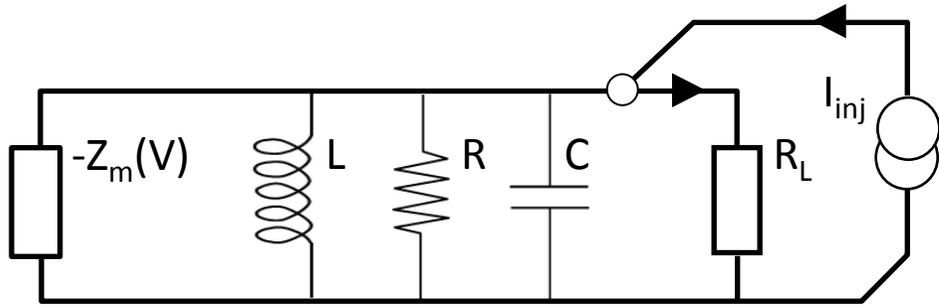
Viatcheslav Pavlov,
Budker Institute of Nuclear Physics (BINP), Novosibirsk, 630090, Russia

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



Permits fast phase control, ~4% fast amplitude control, slow, full range amplitude control





Negative impedance $-Z_m$ to represent magnetron spokes excitation of RF in anode.

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

To get Adler's equation set

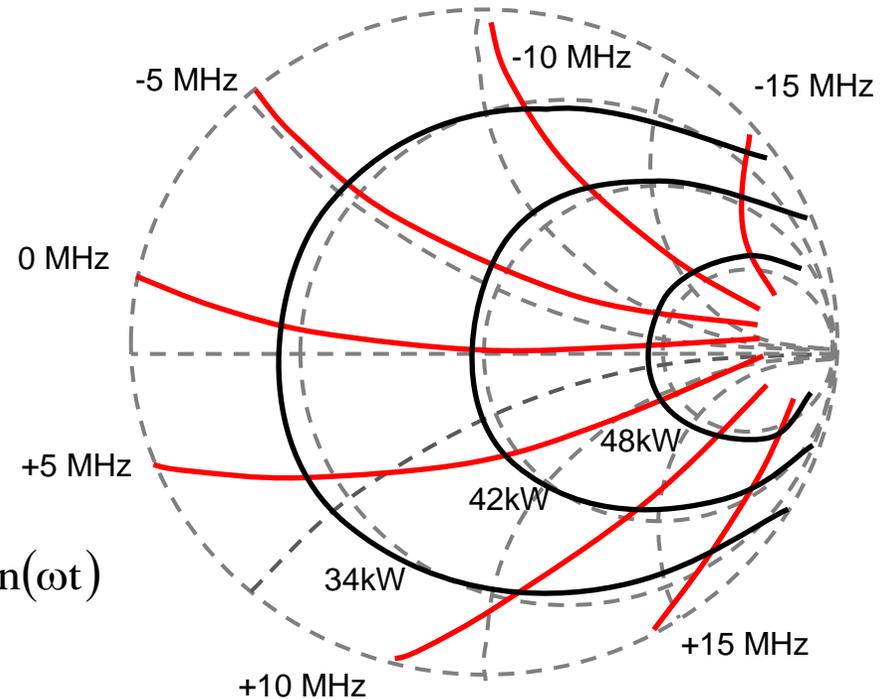
$$V(t) = A(t) \exp\{-j(\omega t + \psi(t))\}$$

Neglect terms to give

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

Bandwidth

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



Rieke diagram plots constant frequency and constant power lines on an admittance chart

$$\text{gain} < \frac{\pi Q_L}{2\omega_o T_{\text{delay}}} \sim \frac{\text{amplifier bandwidth}}{4 \times \text{cavity bandwidth}}$$

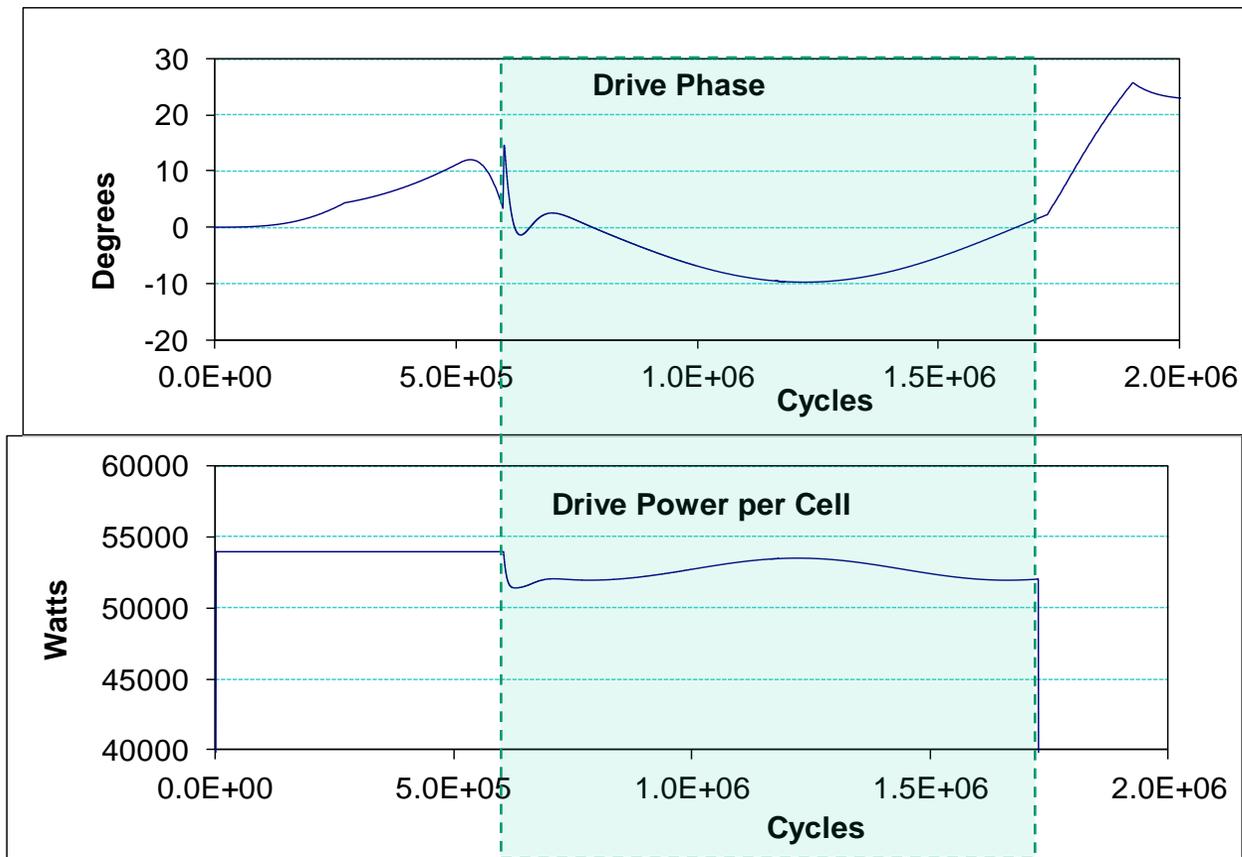
Where T_{delay} is the delay within the controller and amplifier chain in correcting an error.

Freq. (MHz)	Output (kW)	Injection (kW)	Amplification (dB)	Magnetron 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

- Power variation constrained to 4%
- PI control plus simple feed forward when pulse arrives
- Drive power and drive phase depends here on cavity frequency offset caused by a 400Hz microphonic (40Hz shift)

Simulation parameters

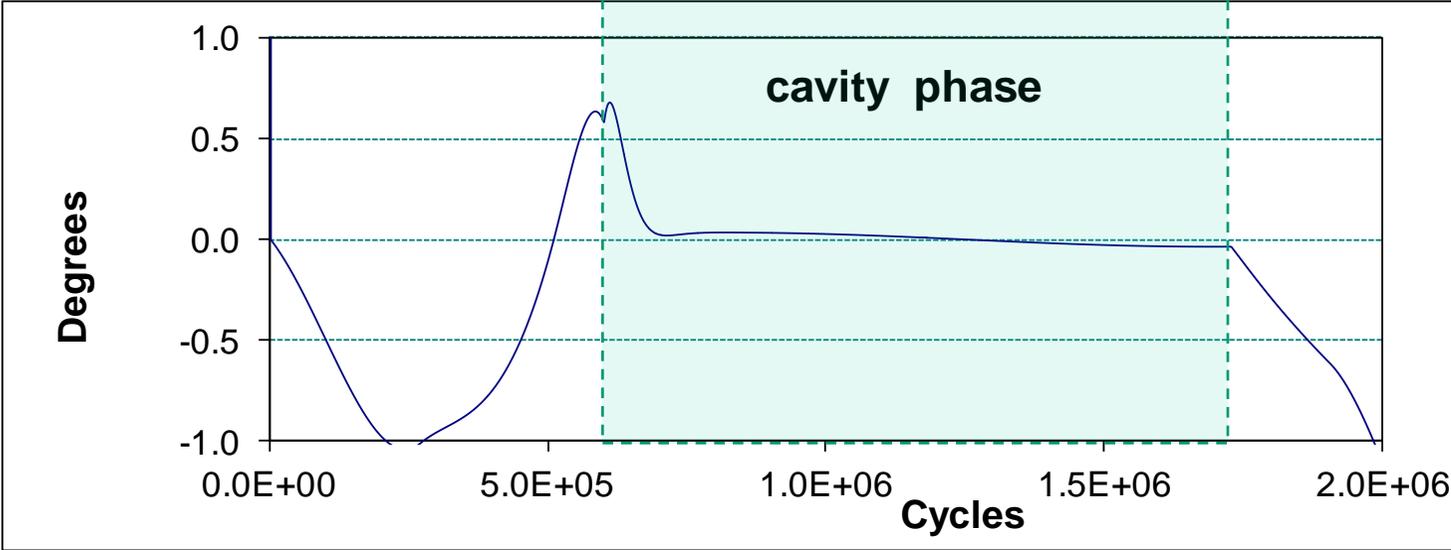
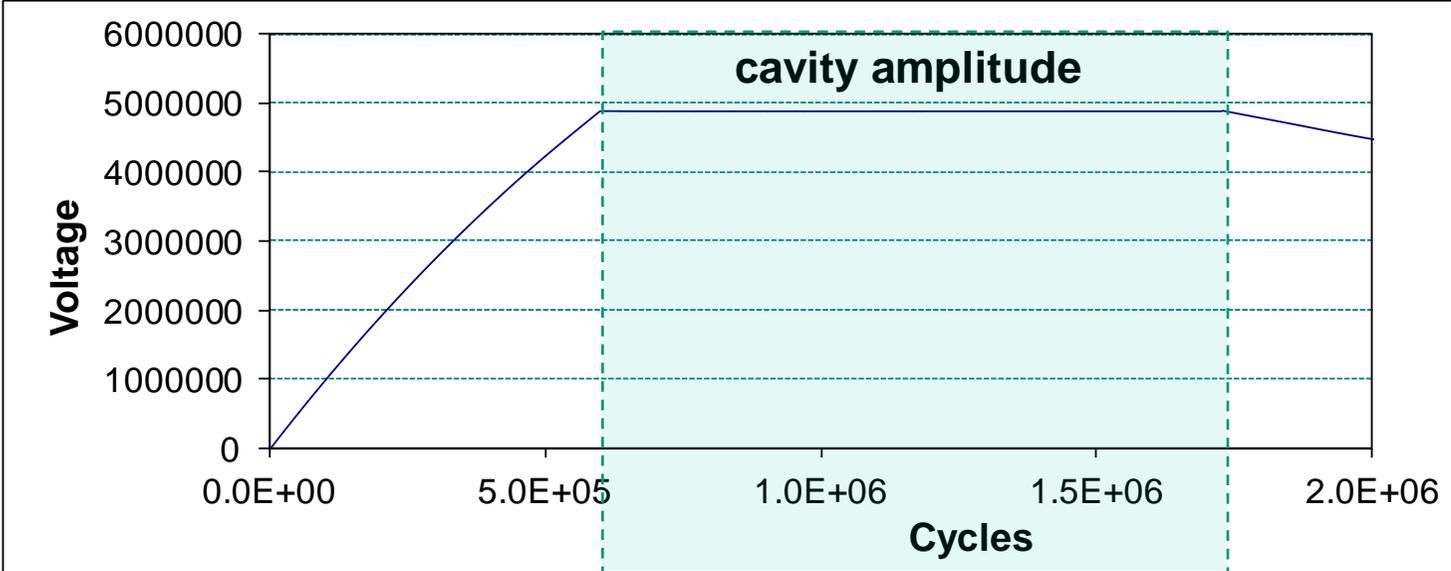
Drive frequency in GHz	= 0.704 GHz
Centre cavity frequency in GHz	= 0.704 GHz
Number of cavity modes included	= 1
Cavity Q factor	= 1.0 E+09
External Q factor	= 4.0 E+06
Cavity R over Q per cell	= 100 ohms
Energy set point	= 21.8 J
Amplitude set point	= 4.8792 MV
Max Amplifier Power per cell	= 54 kW
Max voltage set point (no beam)	= 13.740 MV
Target fill time	= 9.0E-04 s
Cycle number for beam arrival	= 599000
Bunch charge (ILC=3.2 nC)	= 0.057 nC
RF cycles between bunches	= 2
Cavity frequency shift from microphonics	= 40 Hz
Cavity vibration frequency	= 400 Hz
Phase measurement error(degrees)	= 0 deg
Fractional err in amplitude measurement	= 0.0
Time delay (latency) for control system	= 1.0 μs
Control update interval	= 1.0 μs
Gain constant for controller	= 0.55
Beam arrival real feedforward term	= 0.50E+10
Beam arrival imag feedforward term	= 0.13E+10
Amplifier bandwidth	= 1.0 MHz
Measurement filter bandwidth	= 2.0 MHz
In pulse rms phase err	= 0.03217 deg
In pulse rms amplitude err	= 0.00102 %



← Bunch Train →

Simulated Cavity Response

Simulation parameters on previous slide

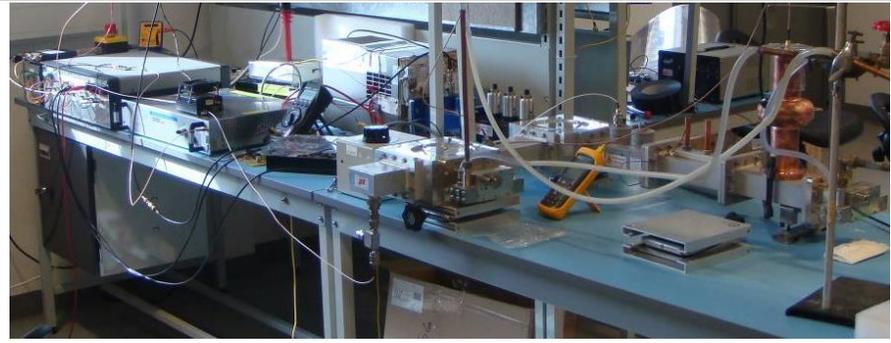
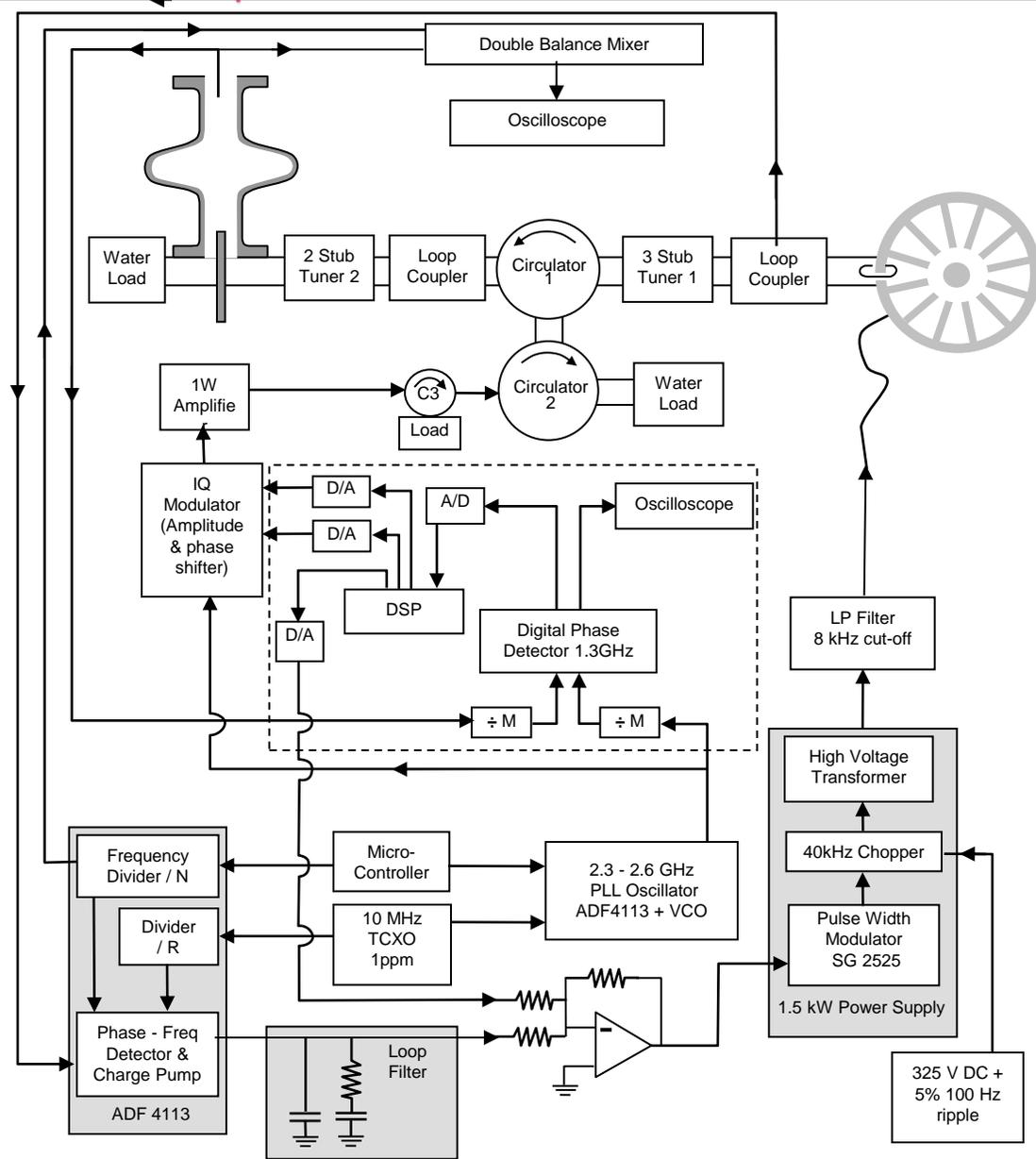


- Intense beams in user facilities need to be generated efficiently.
- Developing a new HPRF source is expensive and comparison to available sources is difficult before development is mature.
- Need accelerator labs to explore new devices at accelerator test stands to have any chance of new devices becoming feasible alternatives.
- Future accelerators constrained on cost so research on efficient low cost sources is worthwhile.

Extra slides



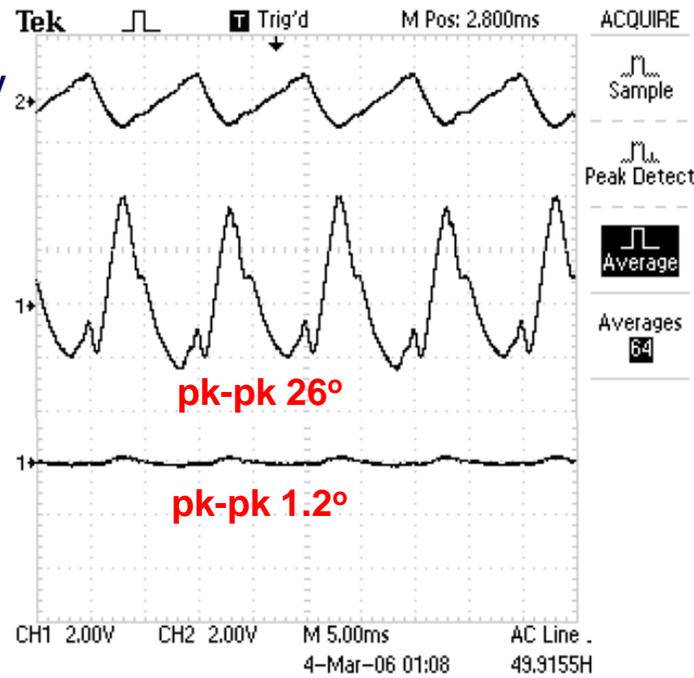
Phase Control in Warm Cavity



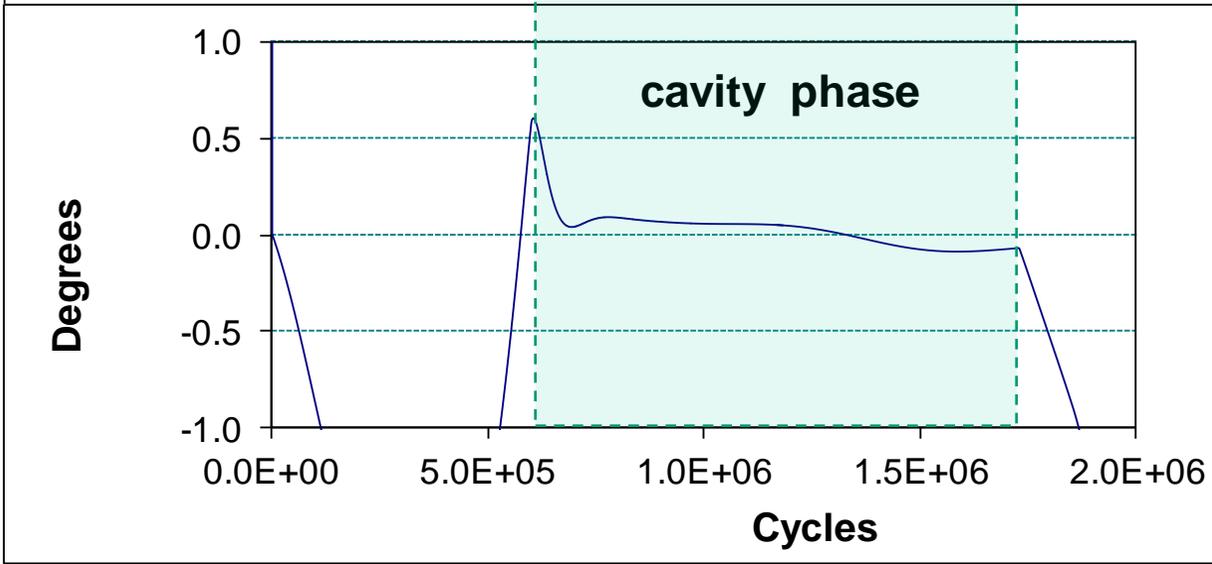
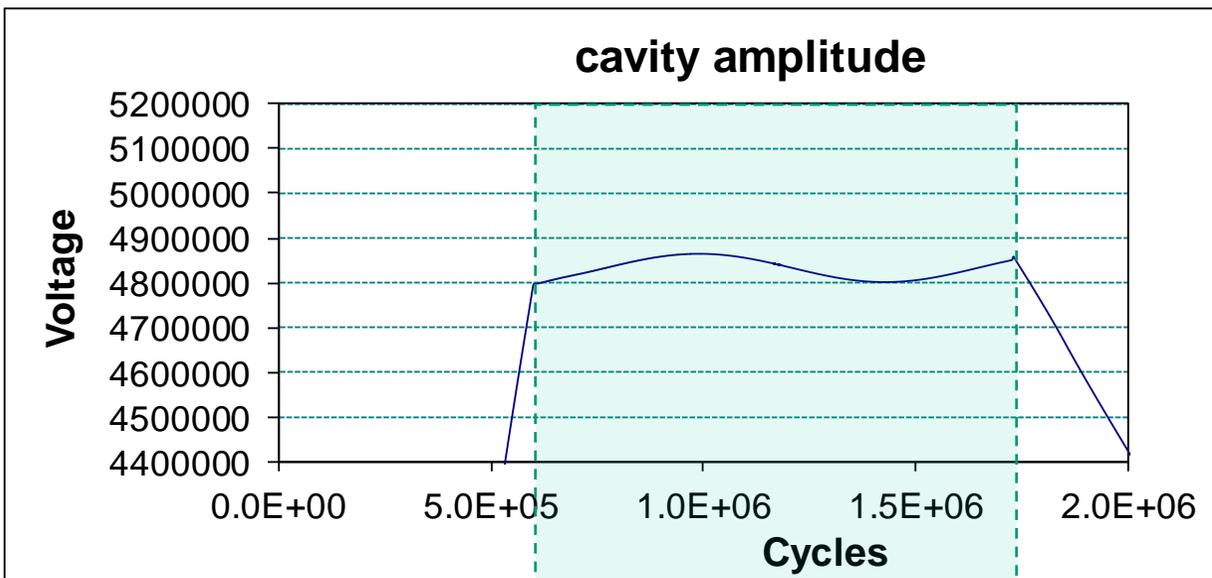
Power supply ripple

Magnetron phase no LLRF

Magnetron phase with LLRF



Increased Microphonics



Increased Microphonics caused power to reach limits and cavity amplitude control is affected

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 per cell	= 100 ohms
Energy set point	= 21.8 J
Amplitude set point	= 4.8792 MV
Max Amplifier Power per cell	= 54 kW
Max voltage set point (no beam)	= 13.740 MV
Cycle number for beam arrival	= 599000
Bunch charge (ILC=3.2 nC)	= 0.057 nC
RF cycles between bunches	= 2
Cavity frequency shift from microphonics	= 70 Hz
Cavity vibration frequency	= 400 Hz
Phase measurement error(degrees)	= 0 deg
Fractional err in amplitude measurement	= 0.0
Time delay (latency) for control system	= 1.0 μs
Control update interval	= 1.0 μs
Gain constant for controller	= 0.55
Beam arrival real feedforward term	= 0.50E+10
Beam arrival imag feedforward term	= 0.13E+10
Amplifier bandwidth	= 1.0 MHz
Measurement filter bandwidth	= 2.0 MHz
In pulse rms phase err	= 0.06363 deg
In pulse rms amplitude err	= 1.03267 %

- Models need to predict the magnetron's negative impedance as a function of Load, Anode Voltage, Magnetic field and Heater Power
- Hopeless task for Particle in Cell Finite Difference Time Domain EM solver codes
- In steady state electromagnetic field mode is known hence EM solver only has to be used once to get mode.
- Fast models track electrons in a self consistent d.c. field that rotates with the spokes plus the RF field times a voltage multiplier

