# PHASE LOCKED MAGNETRONS FOR ACCELERATORS

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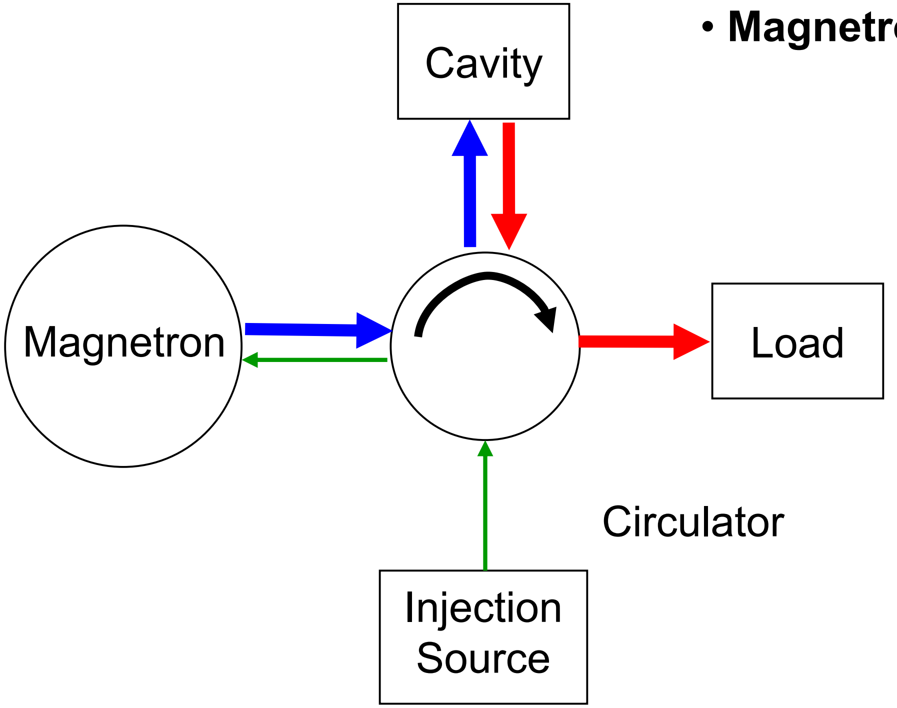
Collaboration on SCRF demonstration

**Lancaster** Imran Tahir, Richard Carter, Graeme Burt

**Jlab** Haipeng Wang, Robert Rimmer, Kirk Davis

# 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
- 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

# 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.**

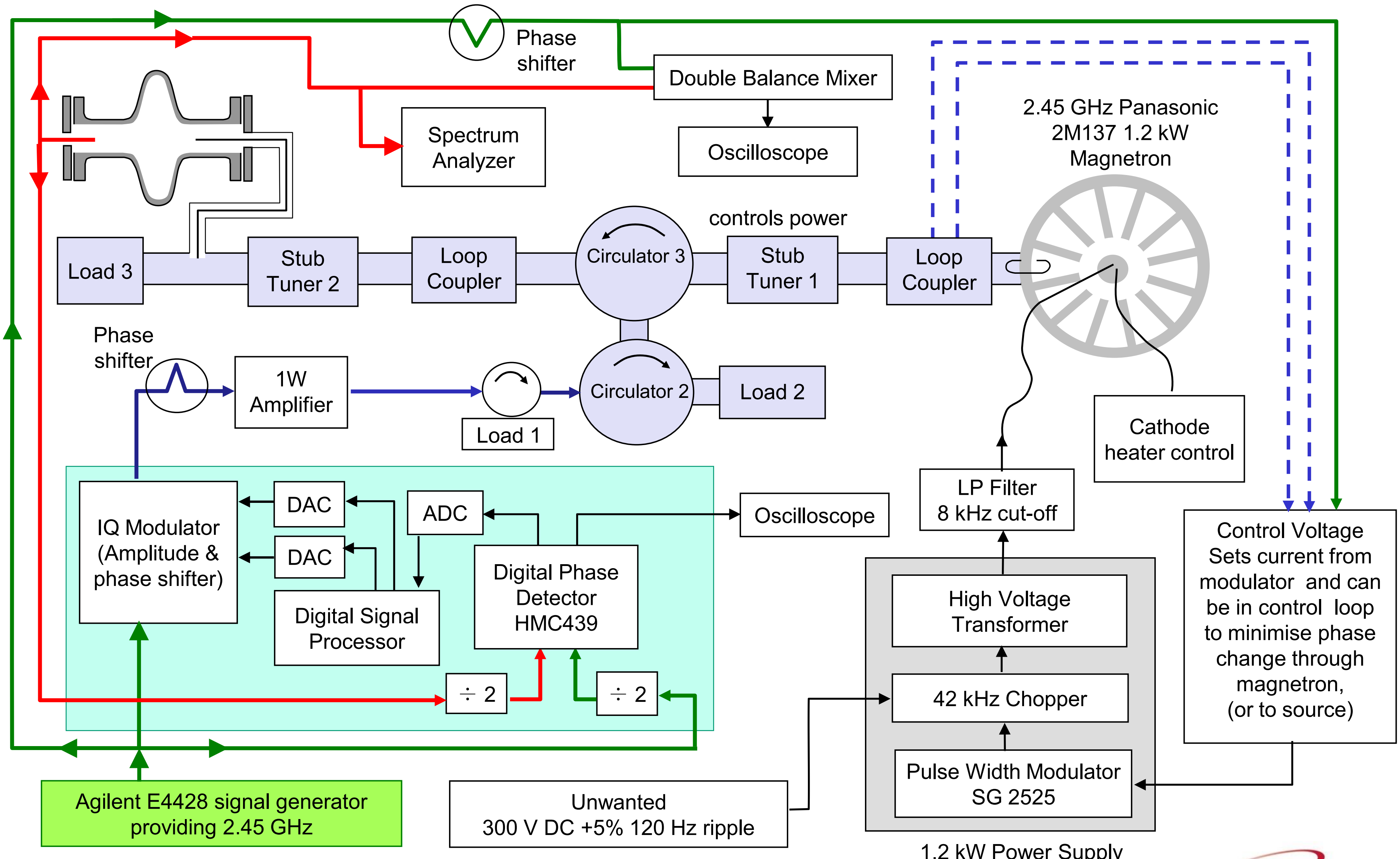
**First demonstration and performance of an injection locked continuous wave magnetron to phase control a superconducting cavity**

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

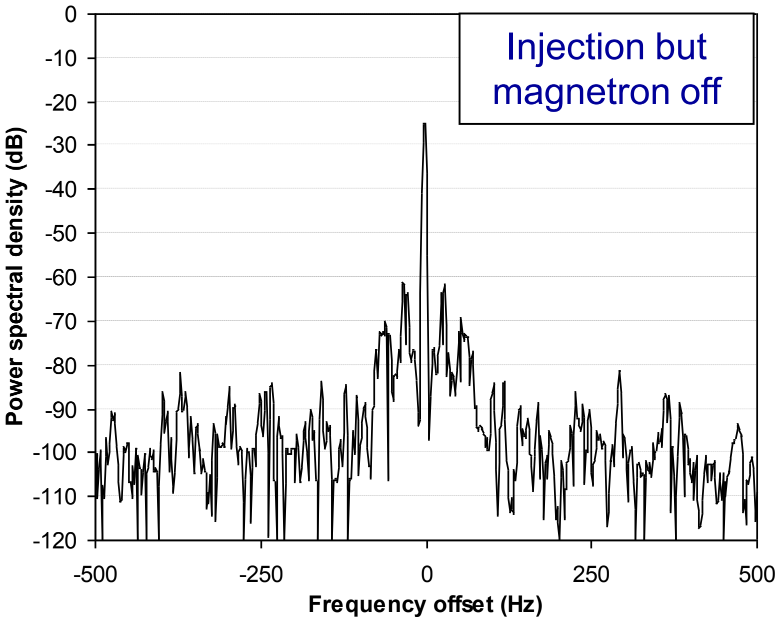
**Physical Review Special Topics: Accelerators and Beams, Vol. 14, No. 3, 17.03.2011, p. 032001.**

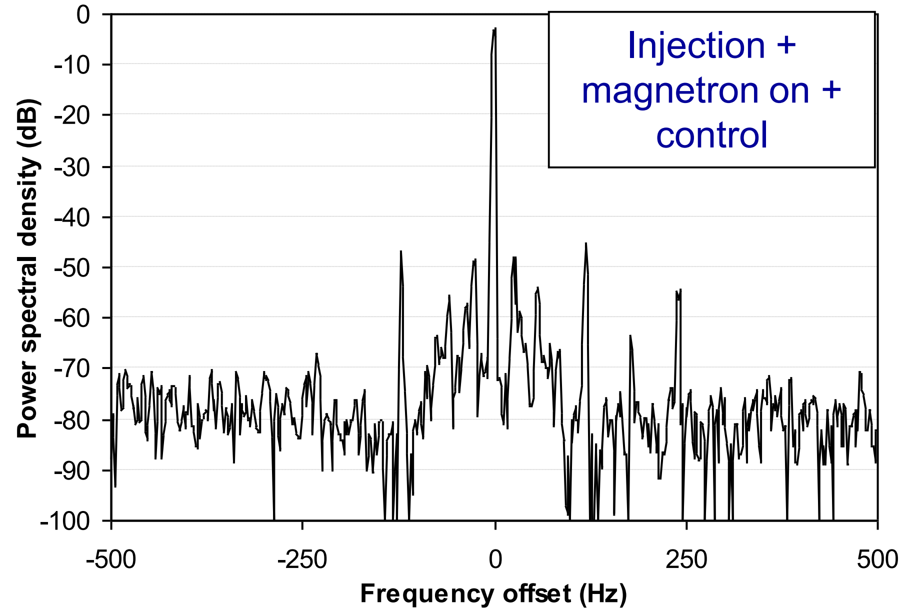
http://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.14.032001

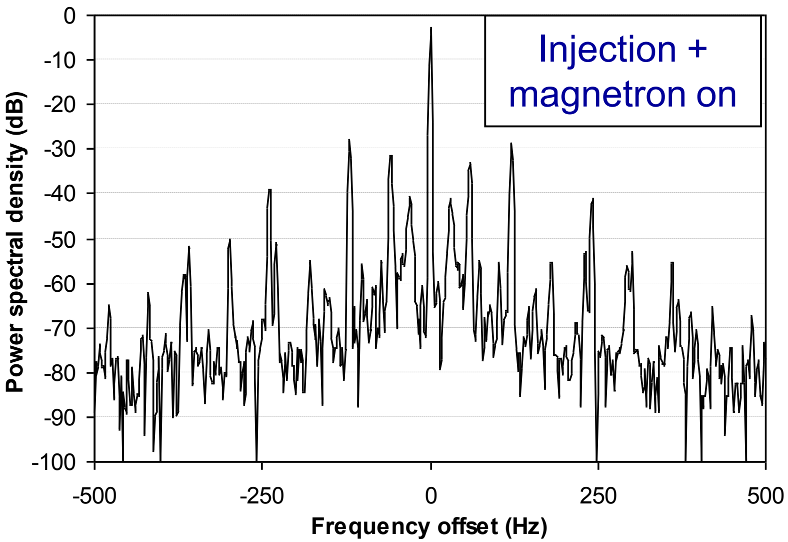
# Circuit for Phased Locked Operation

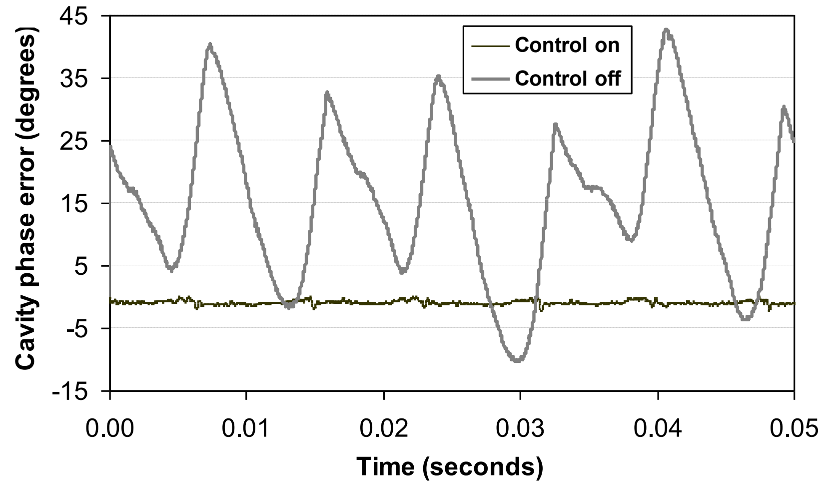


# Phase Control Performance

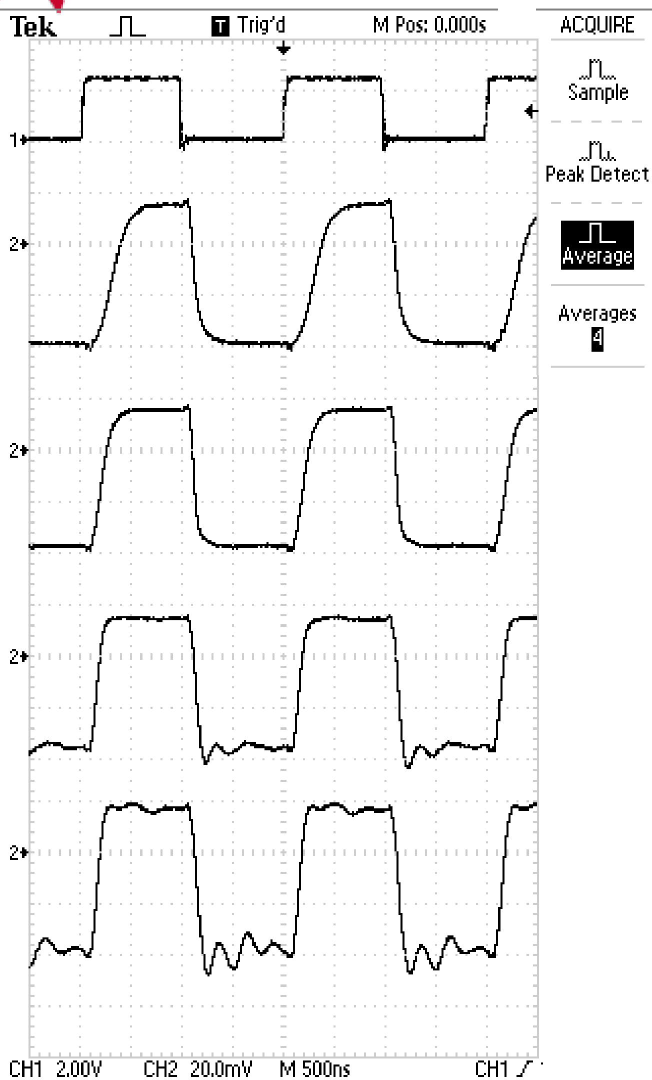


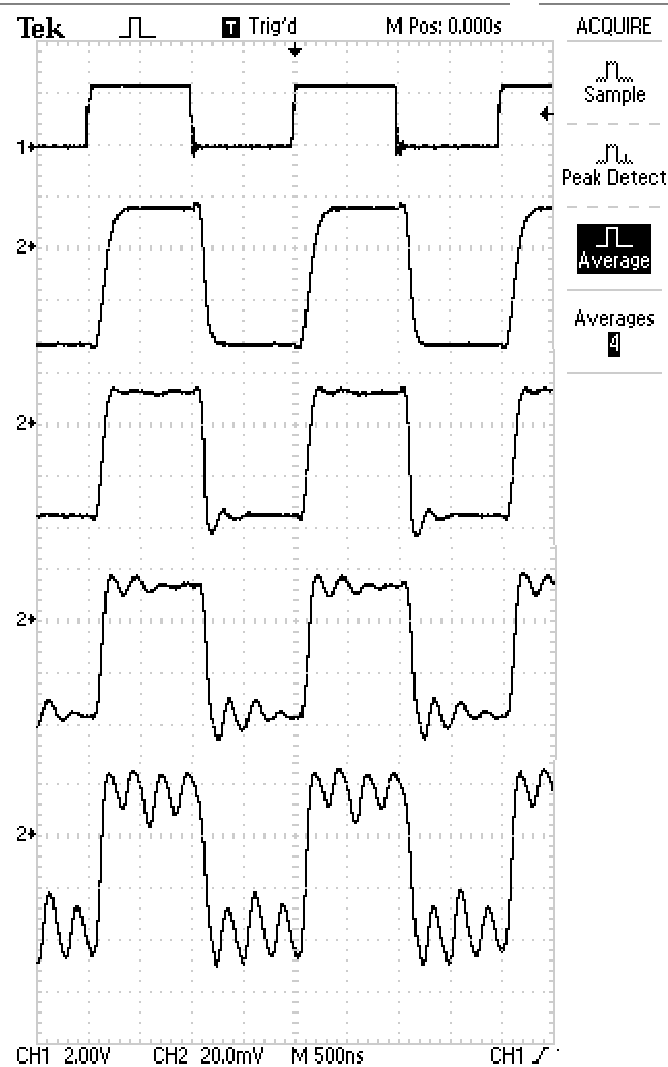



# Response as Function of Heater Power




**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 |

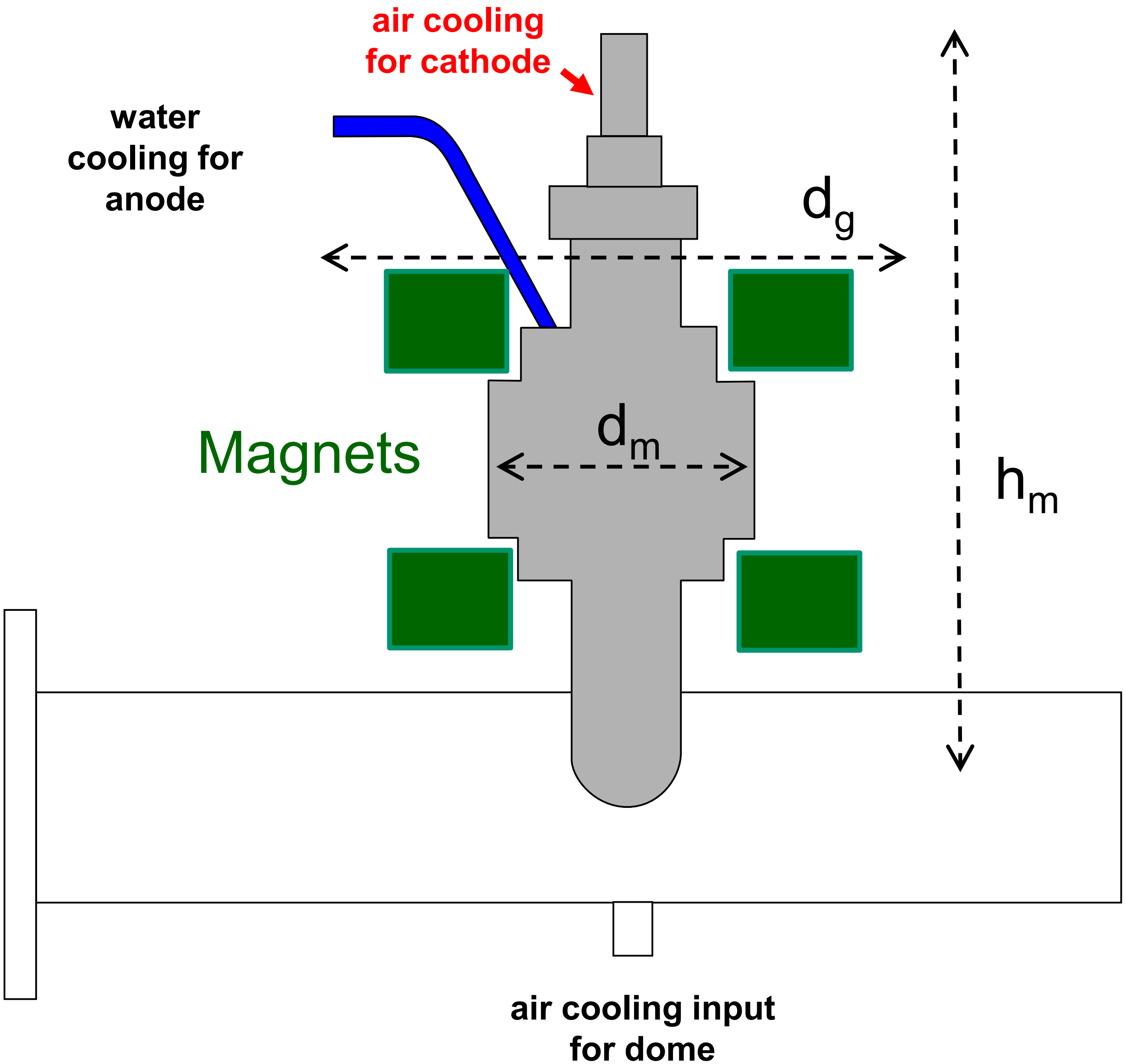
You would not use a magnetron if capital and running costs are not an issue.

# 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.

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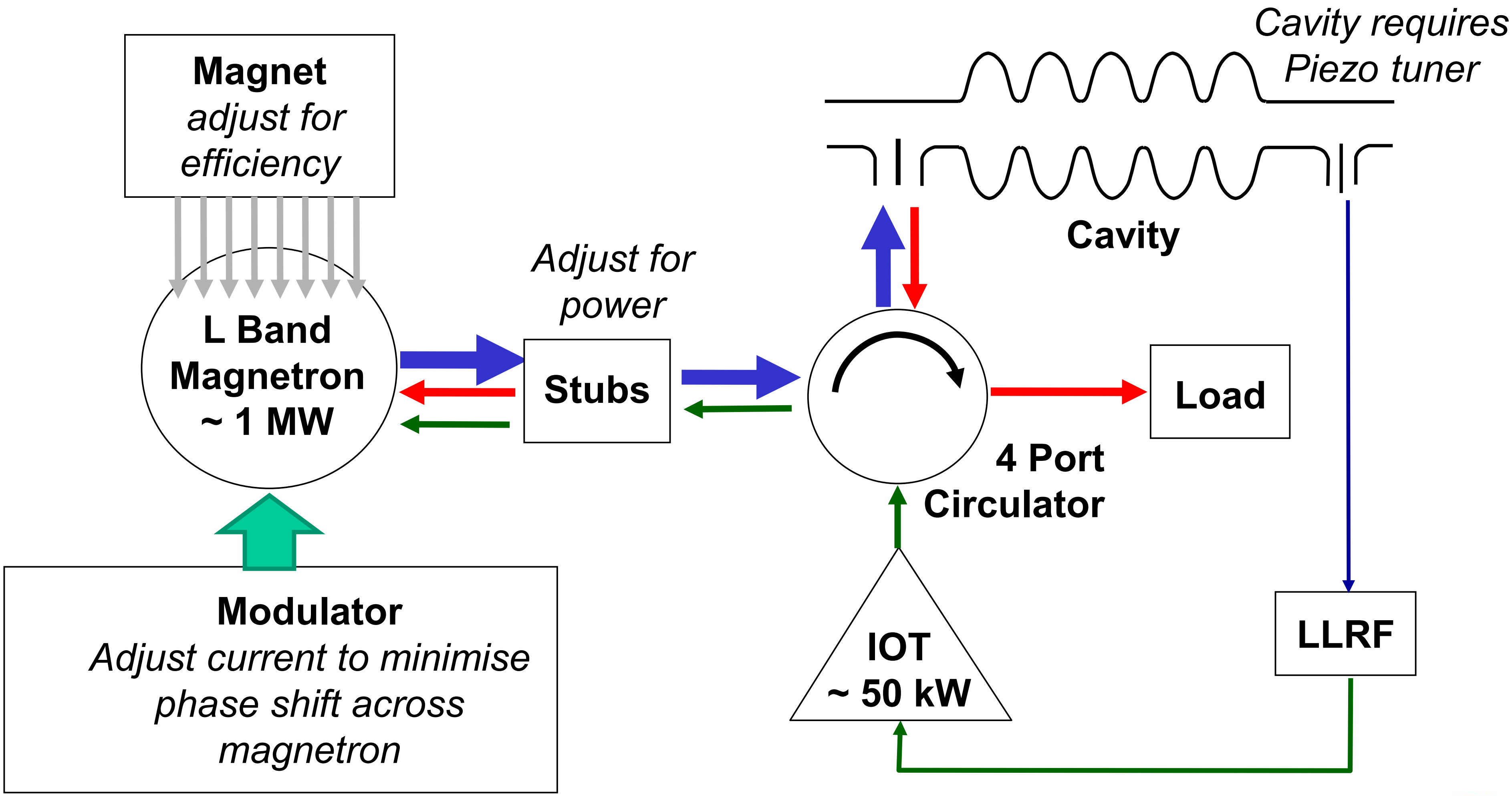
Budker Institute of Nuclear Physics (BINP), Novosibirsk, 630090, Russia

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

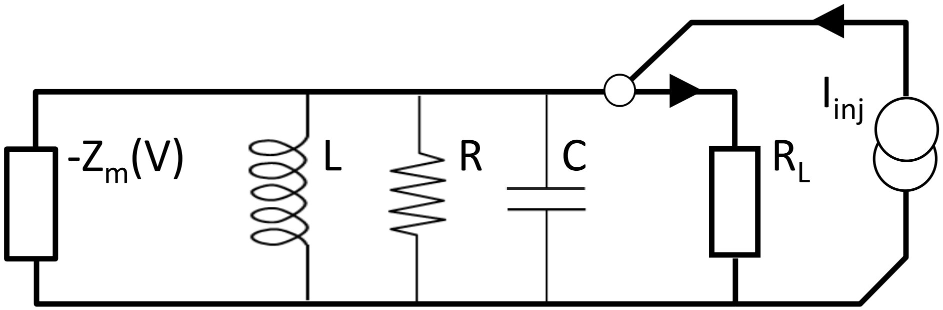
# Low Complexity Layout for Long Pulse Operation



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

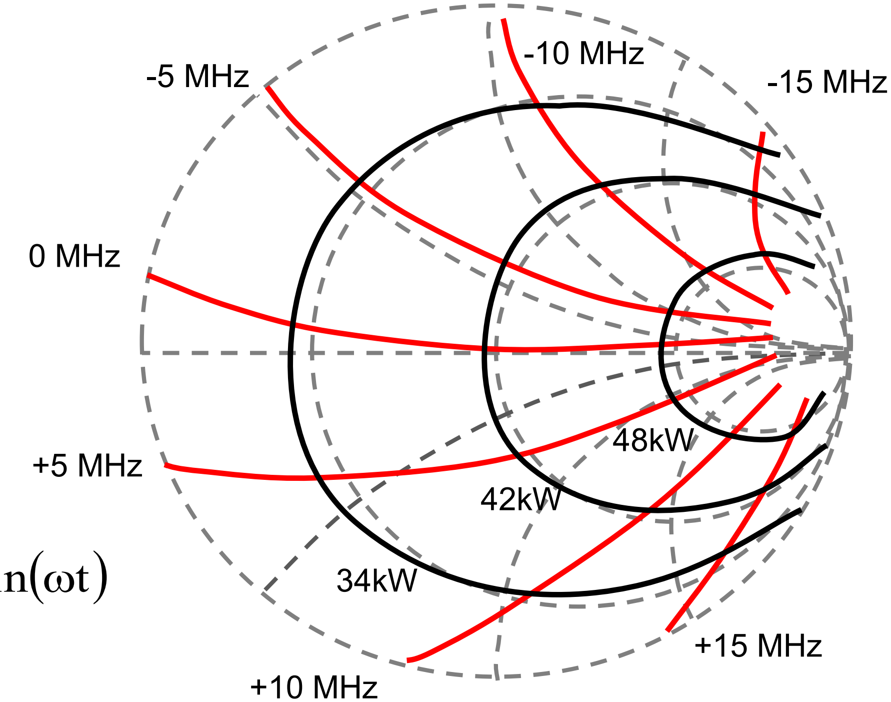


# Magnetron Pulling




**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**



Jefferson Lab

# Bandwidth and Phase Control



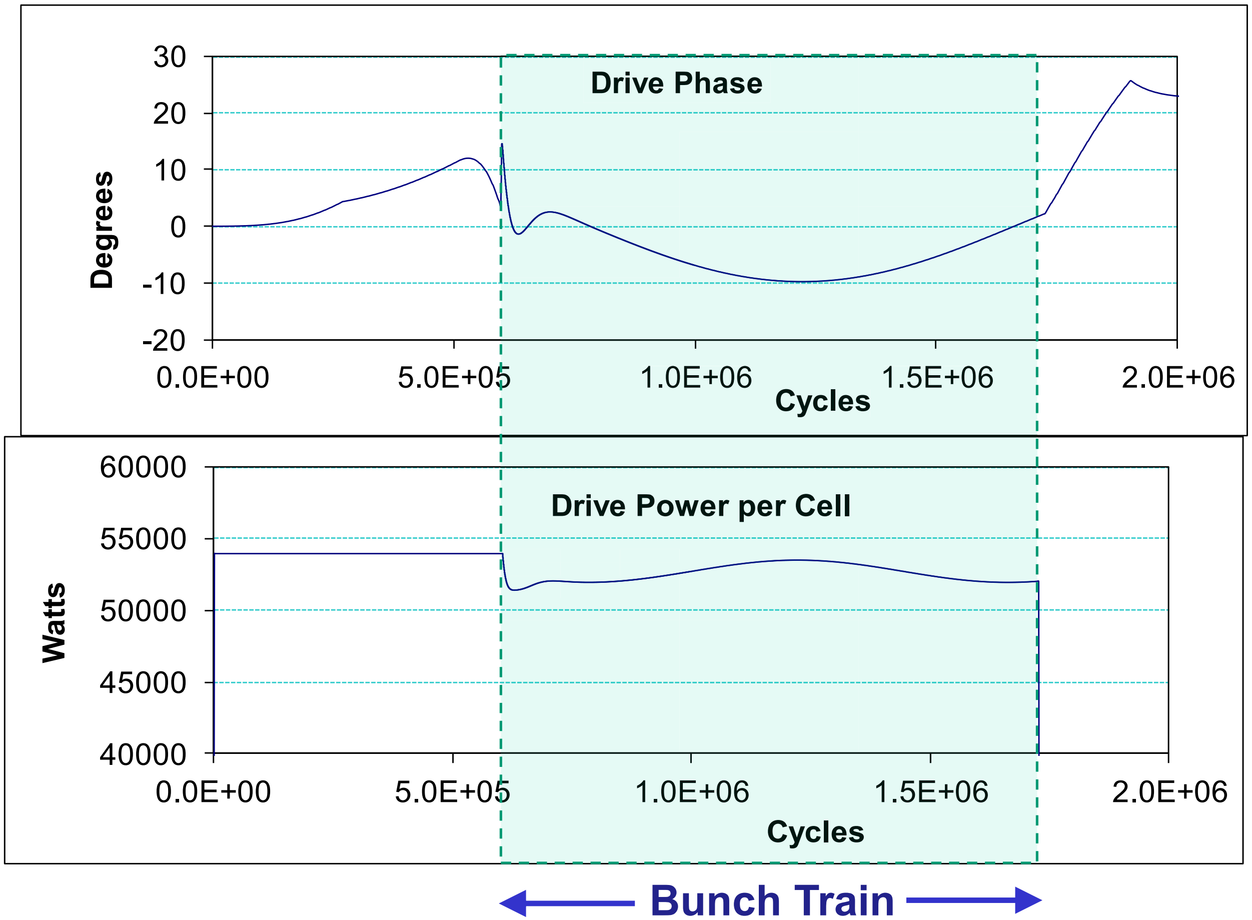
$$\text{gain} < \frac{\pi Q_L}{2\omega_o T_{delay}} \sim \frac{\text{amplifier bandwidth}}{4 \times \text{cavity bandwidth}}$$

**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 |

# Simulation of magnetron driving SPL cavity

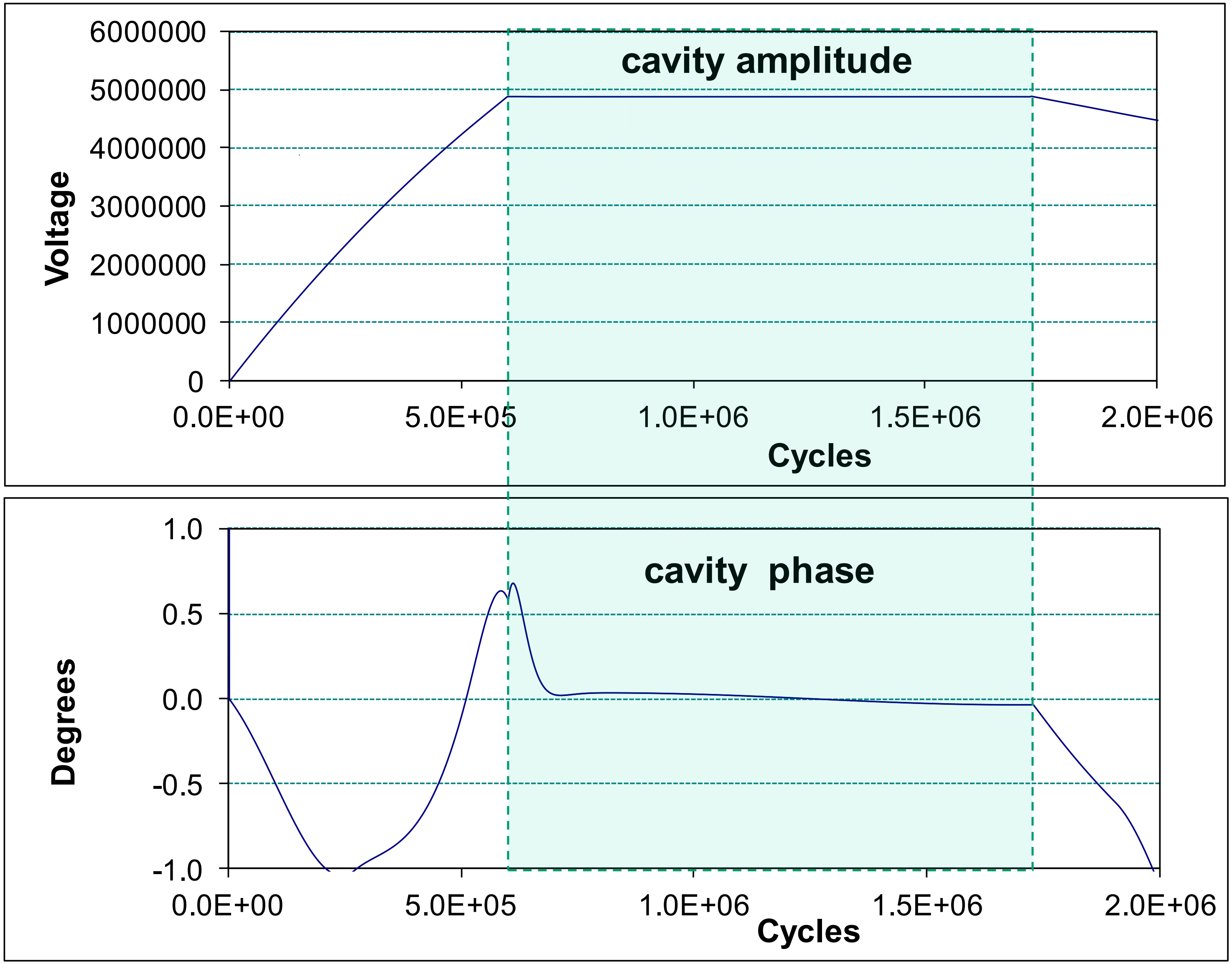
- **Power variation constrained to 4%**
- **PI control plus simple feed forward when pulse arrives**
- **Drive power and drive phase depends here on cavity frequency offset caused by a 400Hz microphonic (40Hz shift)**




## 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 %** |

# Simulated Cavity Response




**Simulation parameters on previous slide**

# 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.
- 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.