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# *ILC Crab Cavity LLRF*

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## *Crab Synchronisation Requirements*

Linac timing requirement is nominally 0.1 degrees at 1.3 GHz ~ 200 fs and hence cannot be relied upon to provide sufficiently accurate timing signals for the crab cavities.

Initial absolute calibration must be adequate to provide reasonable luminosity for initial commissioning of the BDS.

The system must have built in intelligence to self calibrate, to optimise performance and to report that it is functioning correctly.

### *Proposed Scheme*

Provide an interferometer between the crab systems so that the same cavity clock signal is available at both systems.

Synchronise the cavity clock signal to the linac timing signal at one point.

Control crab cavities individually to the interferometer clock signal.

# *Synchronisation Timing*

$$\text{Timing budget} = \frac{\Delta x}{\theta_r c} = \frac{186 \text{ nm}}{0.007 c} \approx 90 \text{ fs}$$

$\Delta x$  = max permissible offset,  $\theta_r$  = half crossing angle = 7 milli-rads

The timing budget might be considered as three equal uncorrelated parts give as  $90 \text{ fs} / \sqrt{3} = 51 \text{ fs}$

Cavity to clock must be synchronised to 51 fs (for each system)

Clock to clock must be synchronised to 51 fs

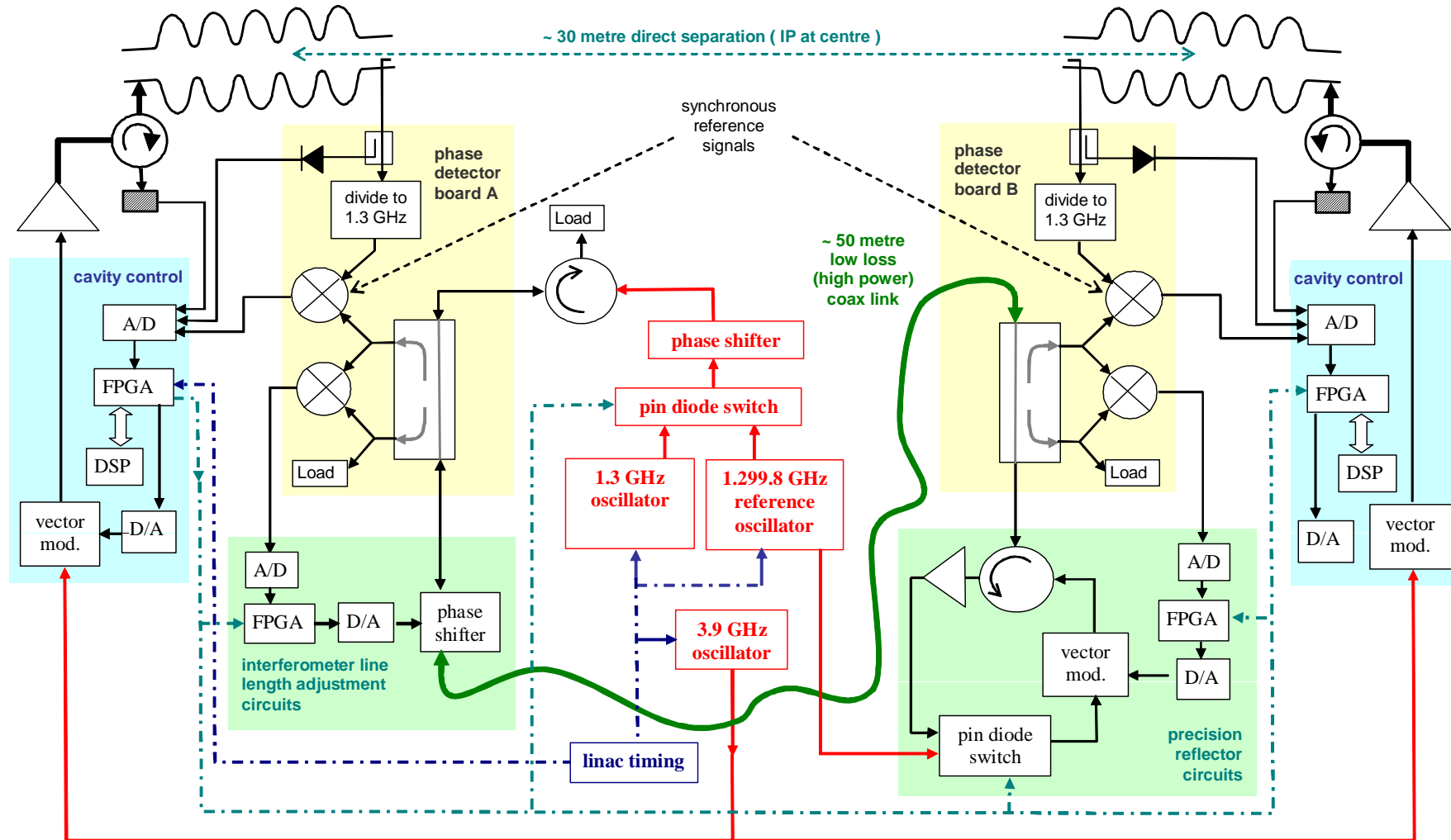
- The clock separation is 50 m hence a 2 ppm expansion of the cable ( $\sim 1^\circ\text{C}$ ) gives a timing shift of 167 fs.
- 50 fs corresponds to  $15 \mu\text{m}$  hence if the synchronisation is to be by dead reckoning then  $15 \mu\text{m}$  is the manufacturing and installation tolerance on a 50 m cable!
- Active control of the effective length of the cable connecting the clocks is an essential requirement.

## *Cavity phase stability requirement at 3.9 GHz*

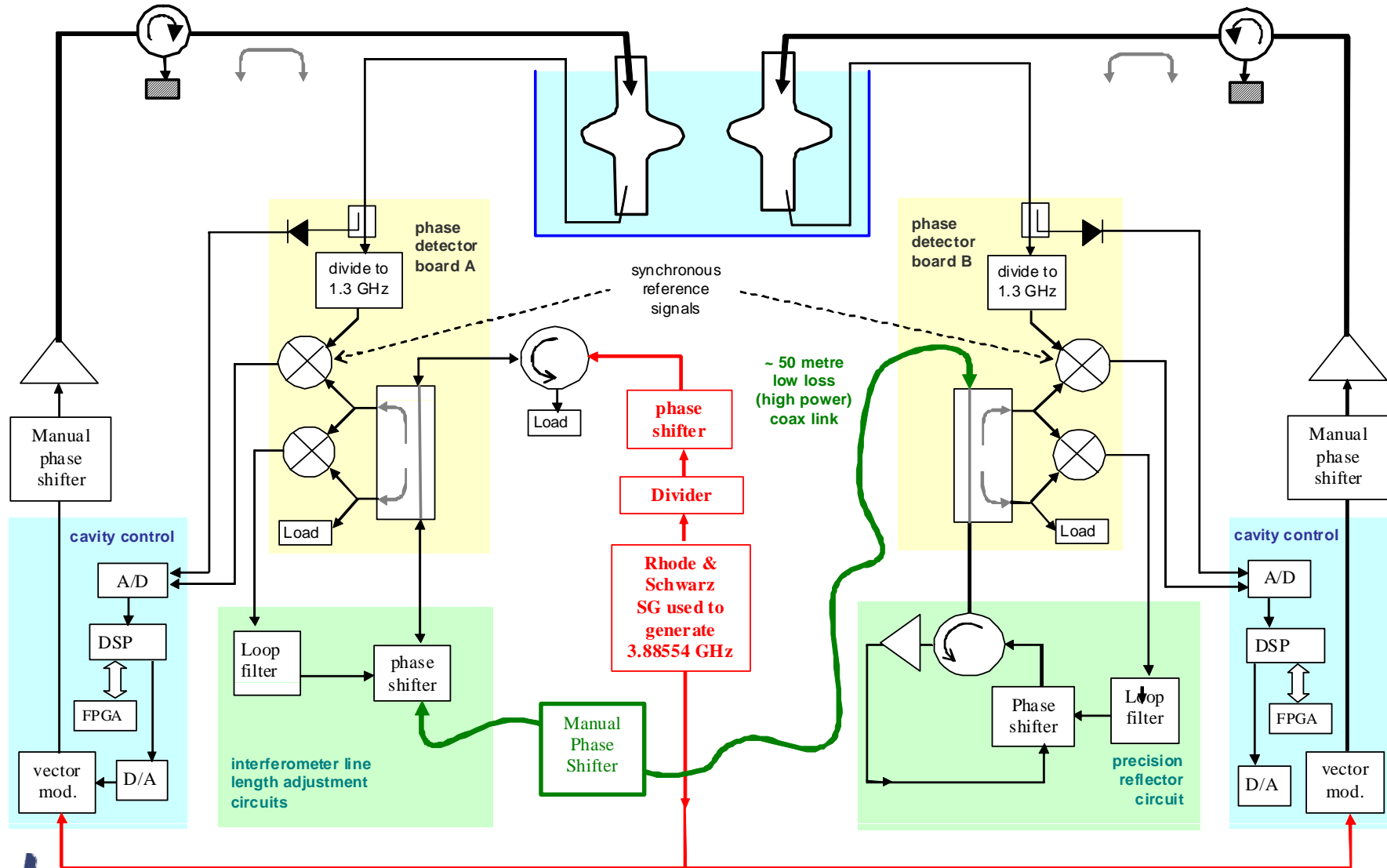
- 51 fs at 3.9 GHz is 0.0716 degrees
- At 3.9 GHz need stabilisation at ~ 70 mdeg (rms) ~ 200 mdeg (pk-pk)
- We are now confident that phase control to this level at this frequency is possible for a crab cavities for envisaged disturbance levels.
- We are confident that an RF spectrometer as opposed to an optical spectrometer can meet the specification (which should also work.)
- The specification can be met with using digital phase detectors
- As an alternative to digital phase detection, results from elsewhere make it apparent that the specification can also be met using digital de-modulation or with a completely analogue system.



# Planned Scheme expected ~ 2010

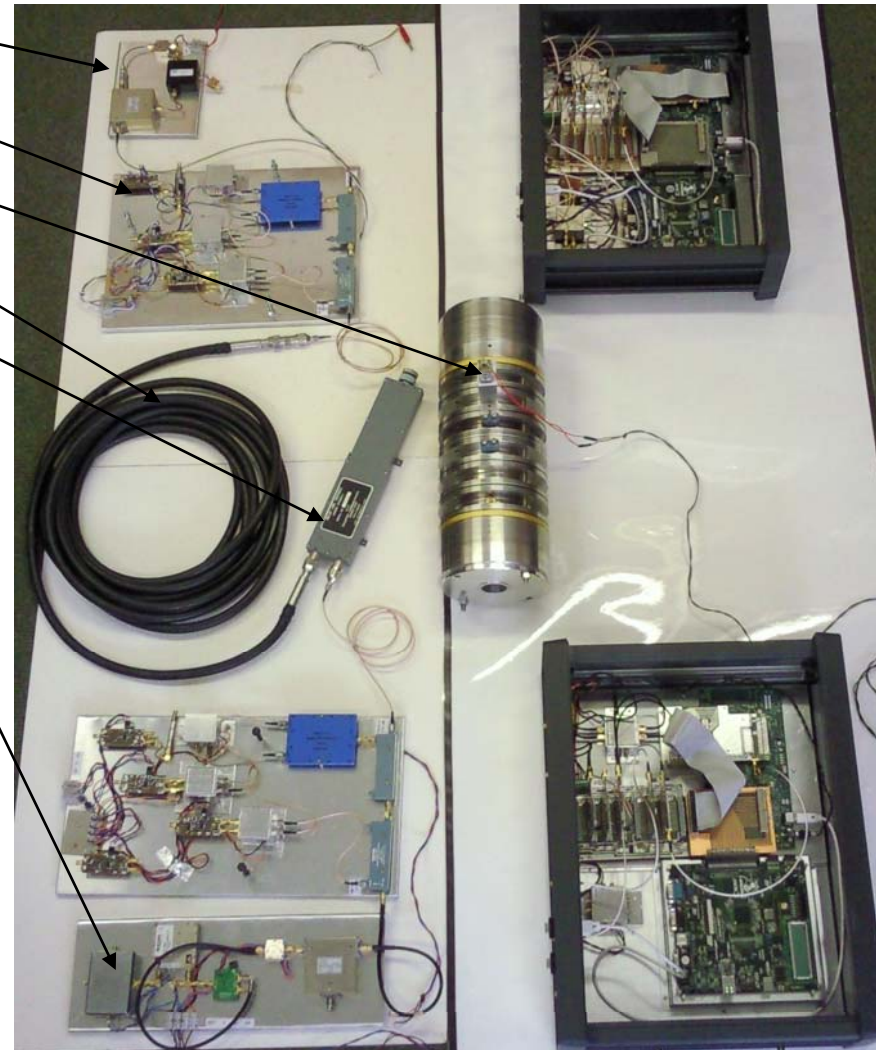
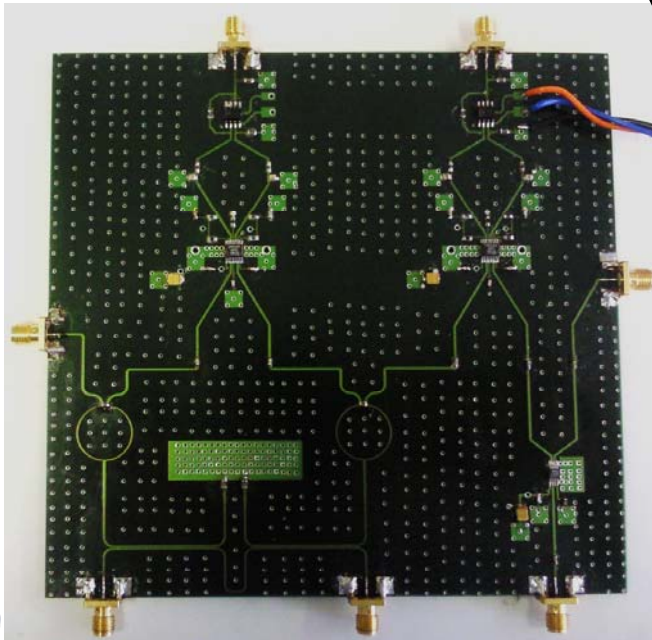


# Scheme used for August 08 tests

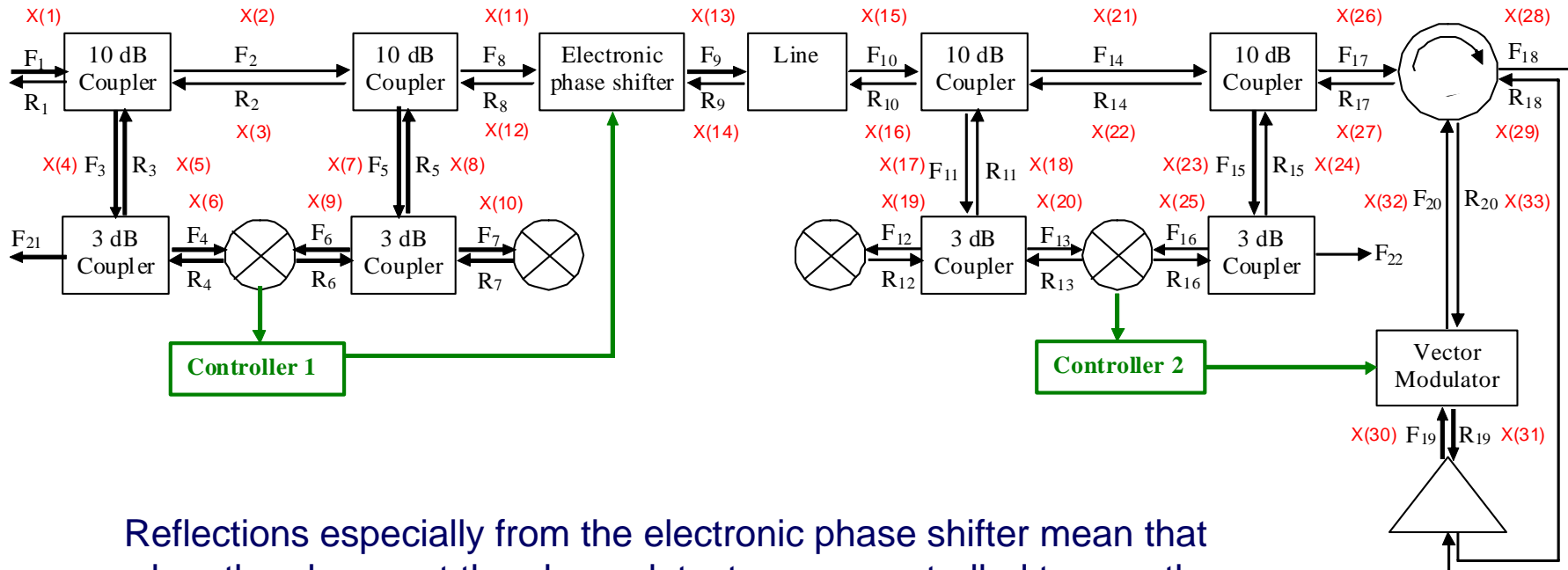


# Interferometer and Control Box Components

- Precision reflector
- Interferometer termination
- Aluminium cavity
- 15m medium loss cable
- Manual phase shifter
- 3.9 GHz source
- Integrated interferometer termination



# Interferometer Model



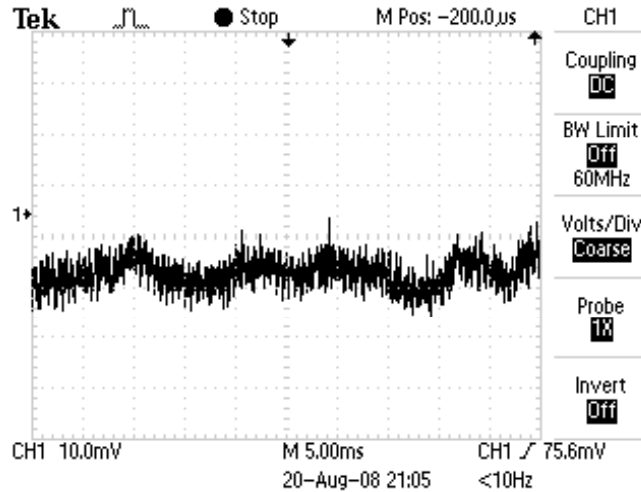
Reflections especially from the electronic phase shifter mean that when the phases at the phase detectors are controlled to zero the actual line length has a small dependency on the correction being made by the electronic phase shifter.

This correction has been computed and measured.





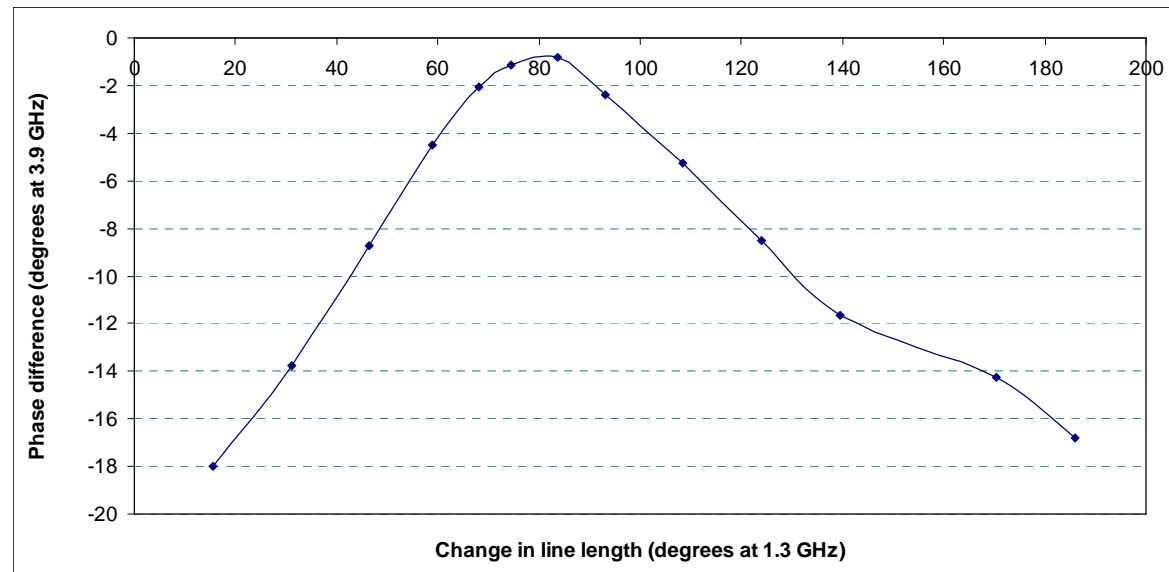
# Phase Lock of Warm Cavities



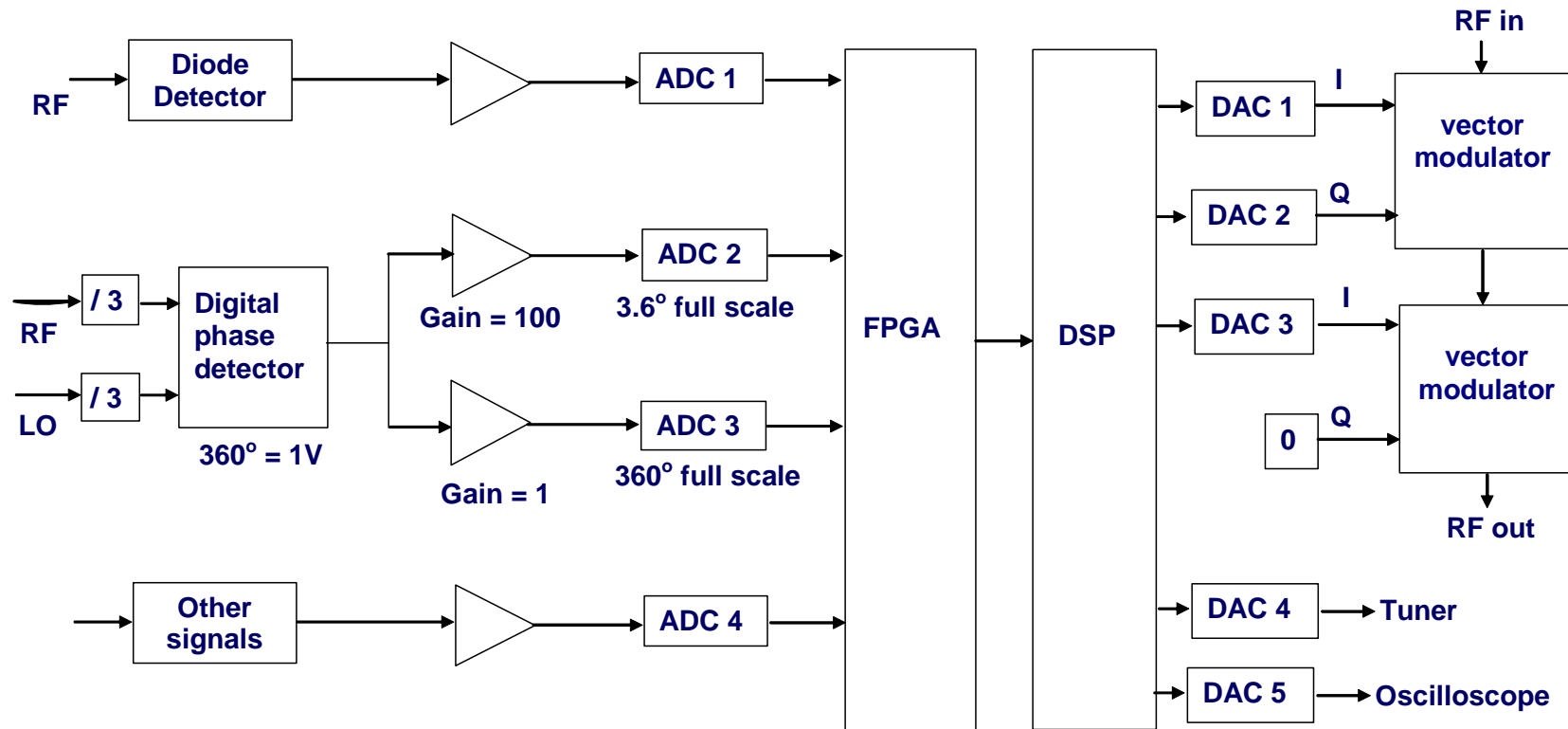
- Calibration at 3.9 GHz is 15 milli-deg per mV.
- The peak to peak jitter in the trace 15 mV
- this converts to 225 milli-degrees pk to pk
- Approximating to 75 milli-degrees r.m.s..

Calibration determined with digital phase detector between cavities and changing the line length with the manual phase shifter.

## Measured Calibration Curve



## Development of 16 bit DAC & ADC Boards



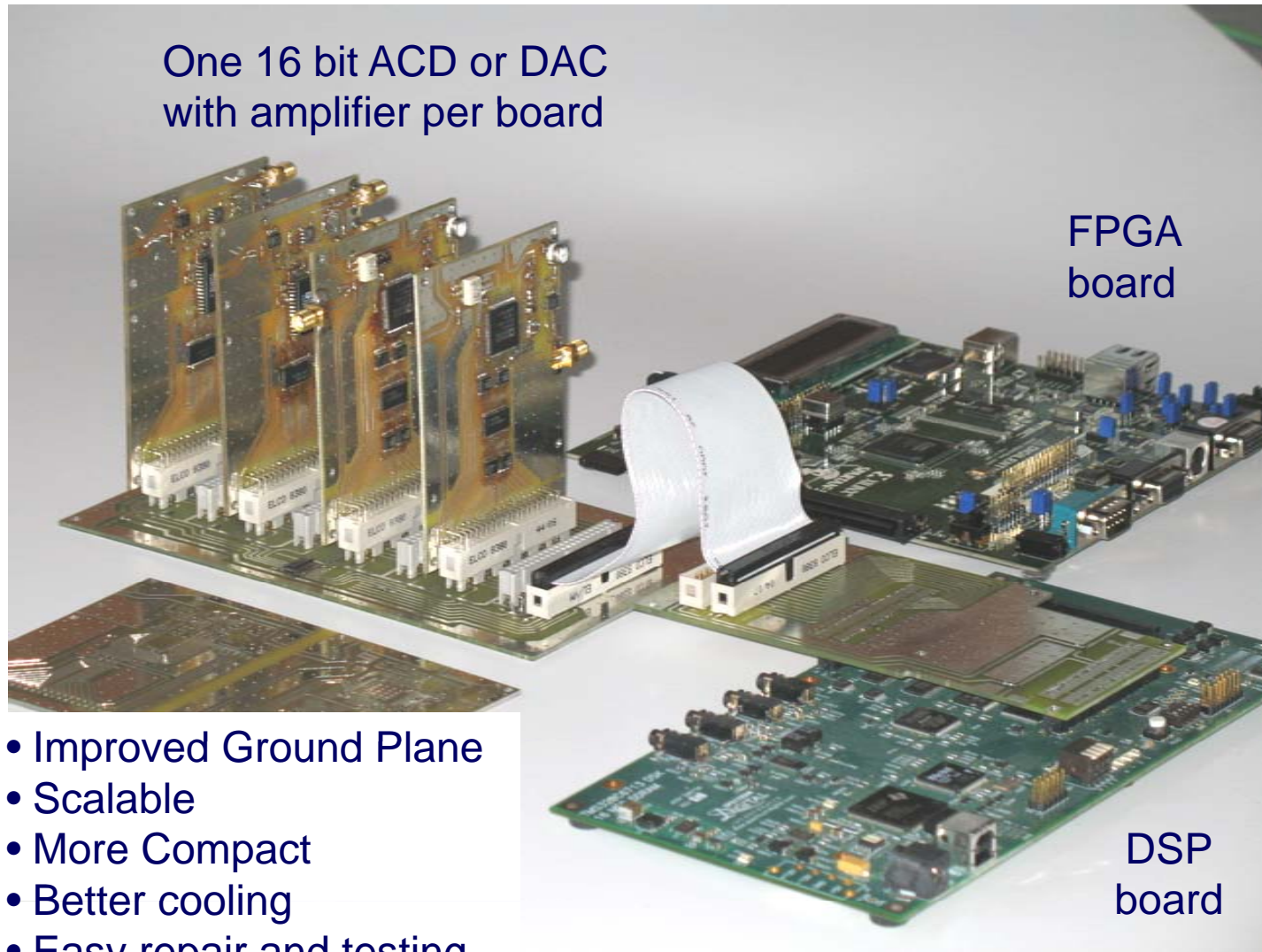
To get the required precision on vector modulation steps the angle should be adjusted before the amplitude is attenuated.

Only 13 of the 16 bits of the A/D are reliable, sample to sample, without averaging, hence full scale only resolves 44 milli-degrees (at 1.3 GHz) sample to sample.



## *New ADC and DAC Modules*

One 16 bit ACD or DAC  
with amplifier per board



- Improved Ground Plane
- Scalable
- More Compact
- Better cooling
- Easy repair and testing

## *Hardware Selection*

### **Phase noise of vector modulator AD8341**

Output noise floor = -150dbm/Hz

2 milli-degrees rms. phase jitter for an input level of 0dbm.

### **Phase noise of 1.3GHz Digital Phase detector HMC439QS16G**

8 milli-degrees rms phase jitter at 1.3 GHz for 1 MHz bandwidth

### **Phase noise of frequency dividers HMC437MS8 (DC-7GHz Divide by 3)**

2 milli-degrees rms phase jitter at 4 GHz

### **Time for calculations in DSP TMS320C6713 (Floating Point)**

Using 360 point look up tables + first order interpolation cosine and sine are both computed in 200 ns

### **Conversion latency and rate in 16 bit ADC converter**

130 ns at 105MSPS

### **Conversion latency and rate in 16 bit DAC converter**

10 ns at 40MSPS

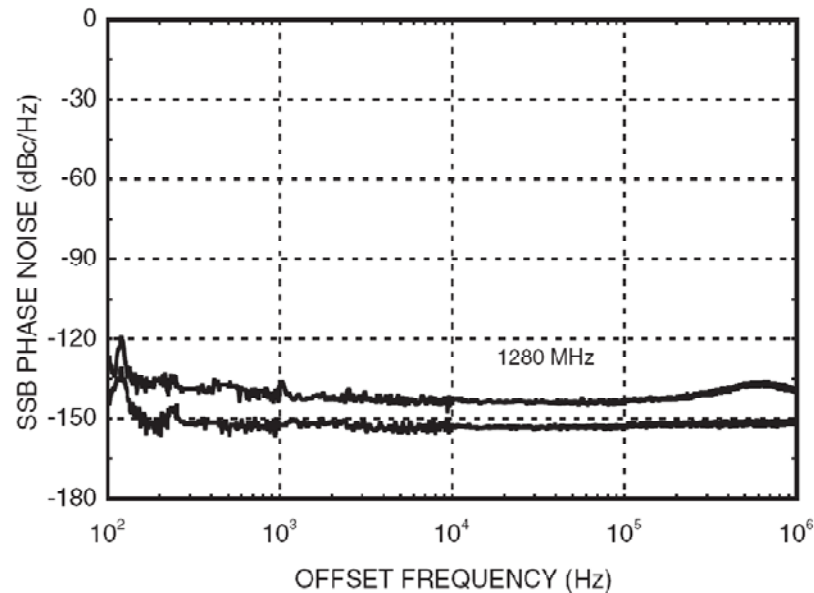
# Hittite HMC439QS16G

Phase noise (1280 MHz) ~ -140 dBc/Hz

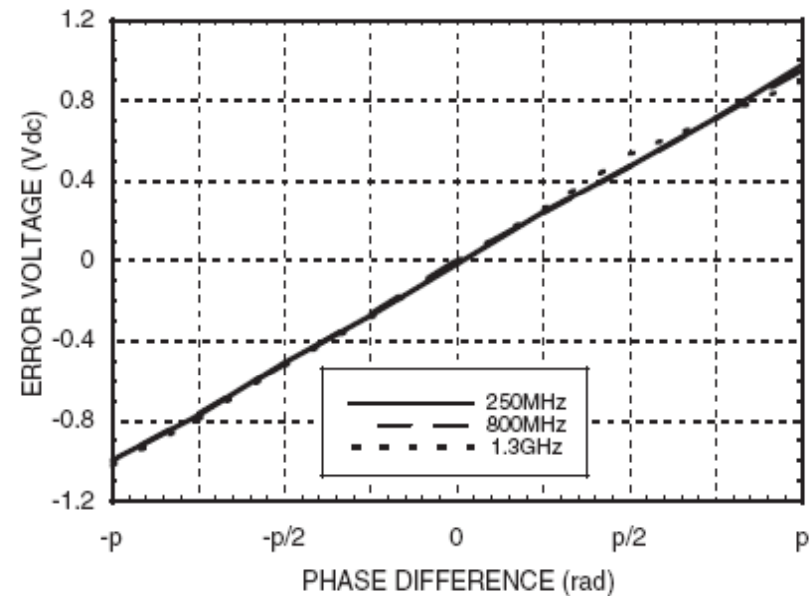
Phase noise (1 MHz bandwidth) ~ -80 dBc

RMS phase jitter =  $1.41 \times 10^{-4}$  radians = 8 milli-degrees = 17 fs

## SSB Phase Noise Performance, $P_{in} = 0$ dBm, $T = 25$ °C



## Error Voltage vs. Frequency, $P_{in} = 0$ dBm\*



## *Features of Control System Hardware*

1. The phase detector boards have uncontrolled lengths, they must be extremely stable and must sit on the end of the couplers.
2. Cavity control loop latency limits the useable gain and hence the performance. It is preferable to have the high power amplifiers within 10 m of the cavity ( $2 \times 10 \text{ m} \sim 66 \text{ ns}$  from a budget of about 1000 ns)
3. The scheme plans to use digital phase detectors which can be calibrated together with their amplifiers and D/A converters by sweeping the input phase through  $360^\circ$ . In order to sweep the phase on each detector a second oscillator shifted slightly from the first is required.
4. Currently high quality digital phase detectors are only available to 1.3 GHz and hence the interferometer runs at this frequency.
5. Systematic errors arise in the interferometer from reflection. A vector modulator is used in the precision reflector so that the return signal can be amplitude modulated. This will allow some systematic errors to be removed.



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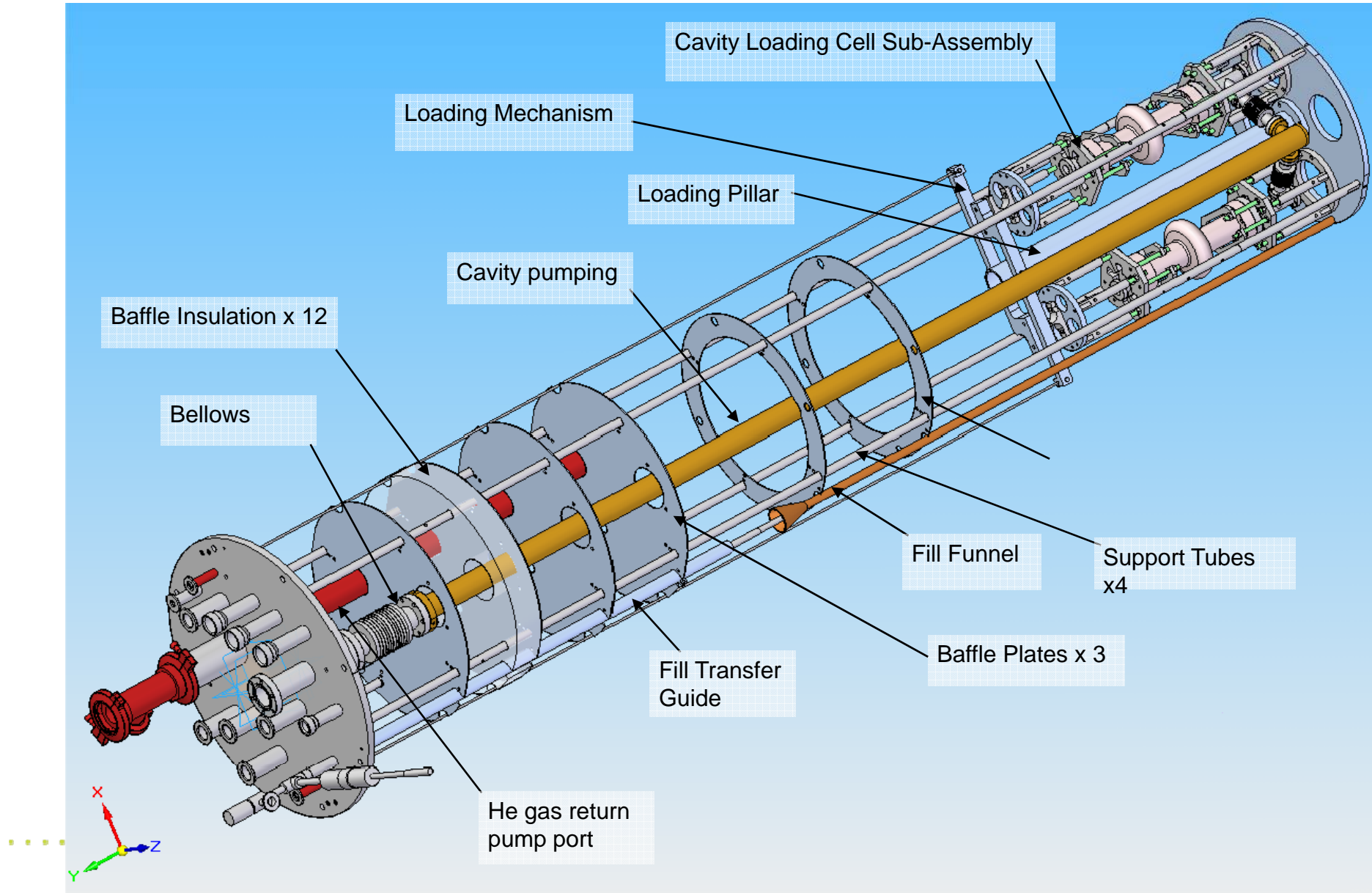


# *Vertical Cryostat*





# *Cavity Support Assembly*







# Tuner Issues



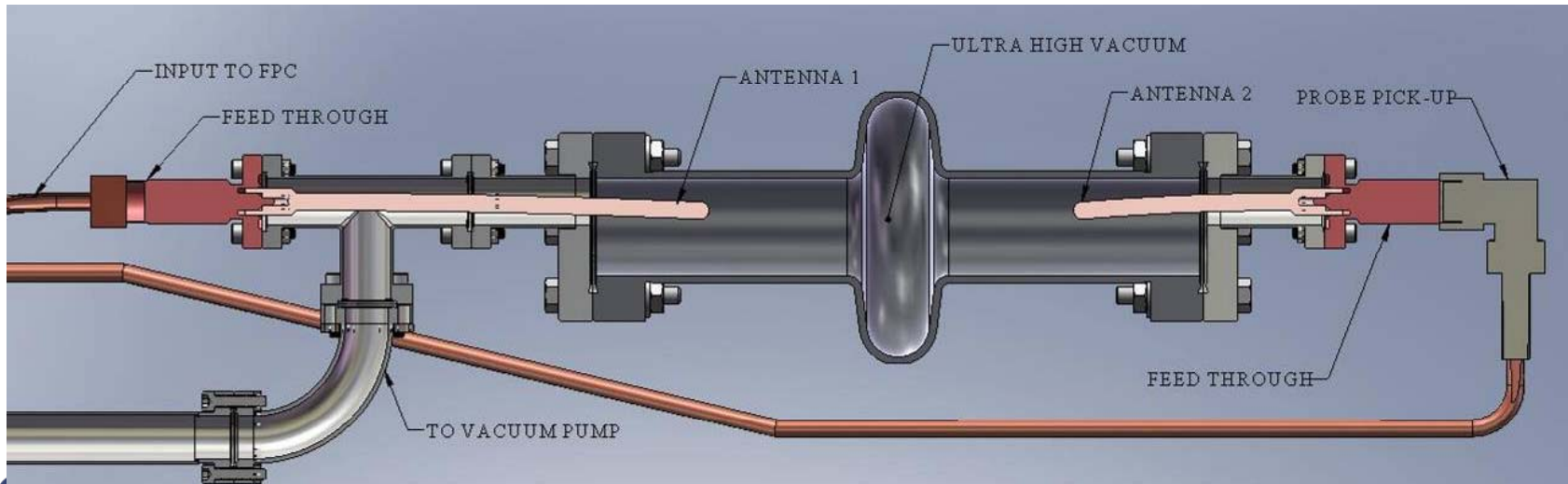
## Cavity 1

QL = 0.97e7  
Q<sub>e</sub> (input) = 1.44e7  
Q<sub>e</sub> (output) = 3.0e9  
Q<sub>o</sub> = 3.0e7  
Bandwidth = 400 Hz  
Drift ~ 300 Hz  
Not Tuneable

## Cavity 3

QL = 1.52e7  
Q<sub>e</sub> (input) = 2.57e7  
Q<sub>e</sub> (output) = 9.6e9  
Q<sub>o</sub> = 3.7e7  
Bandwidth = 600 Hz  
Drift = 5 kHz to 20 kHz  
Small tuning range

At best only able to lock both cavities for a minute

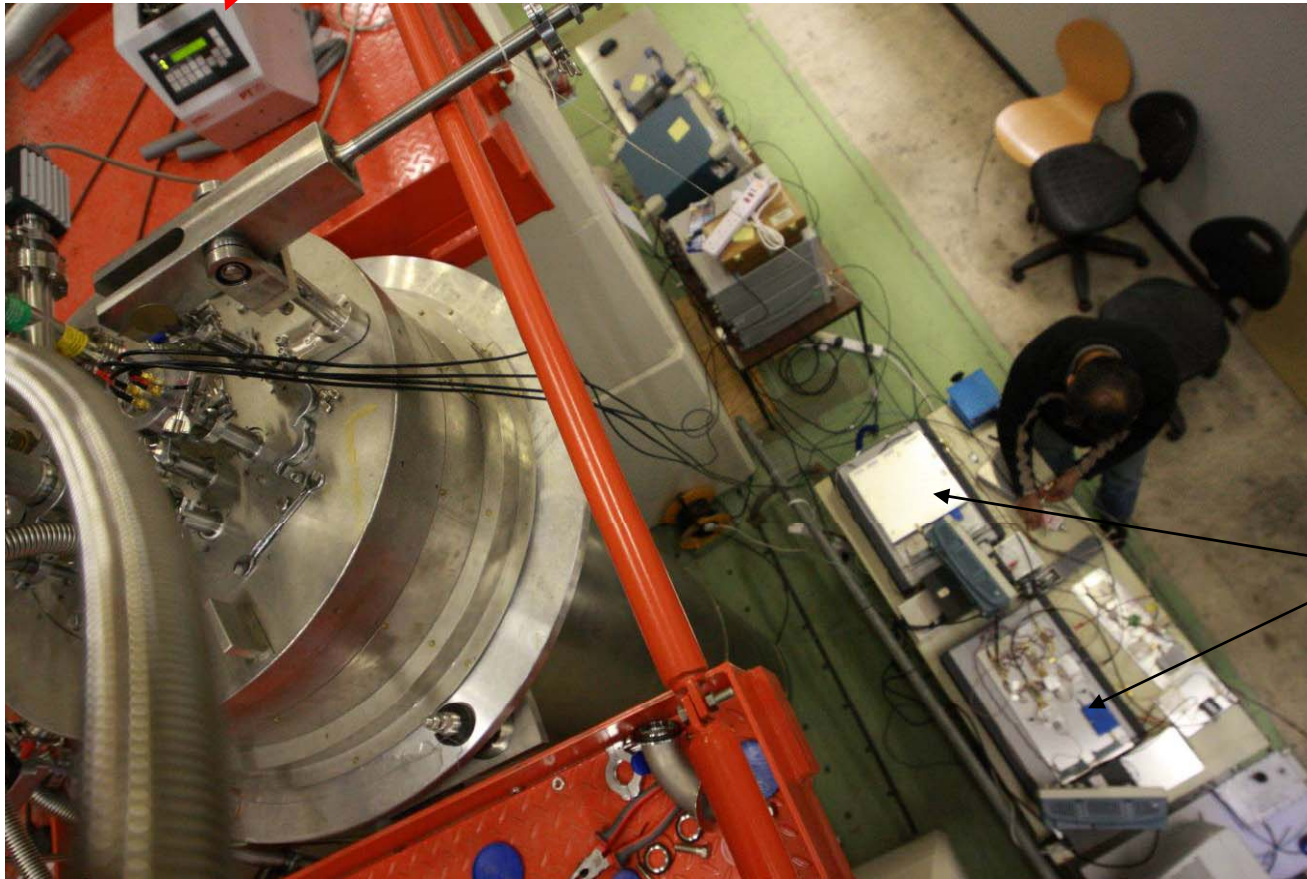




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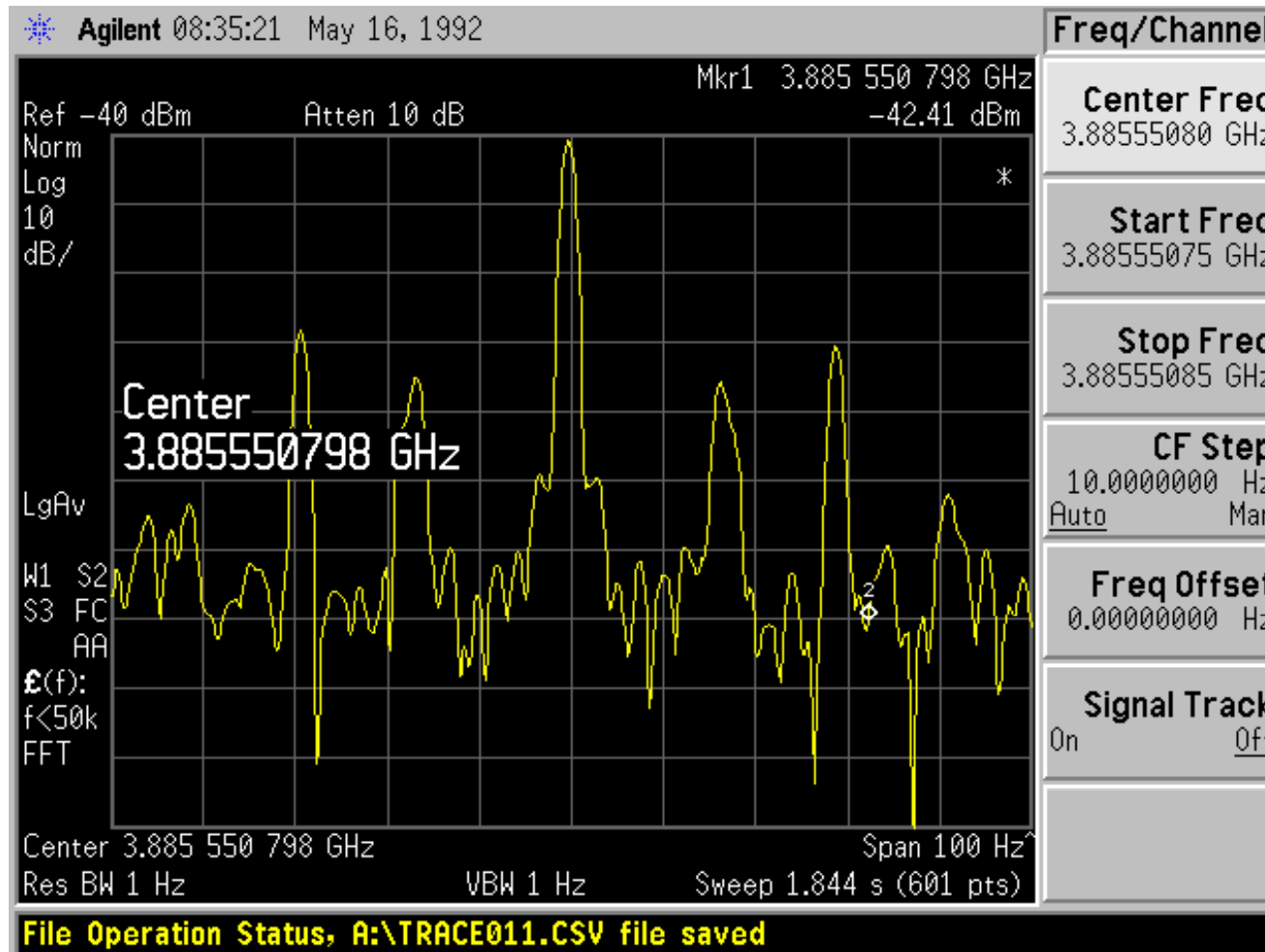


# *Vacuum Pump – Microphonic Source*



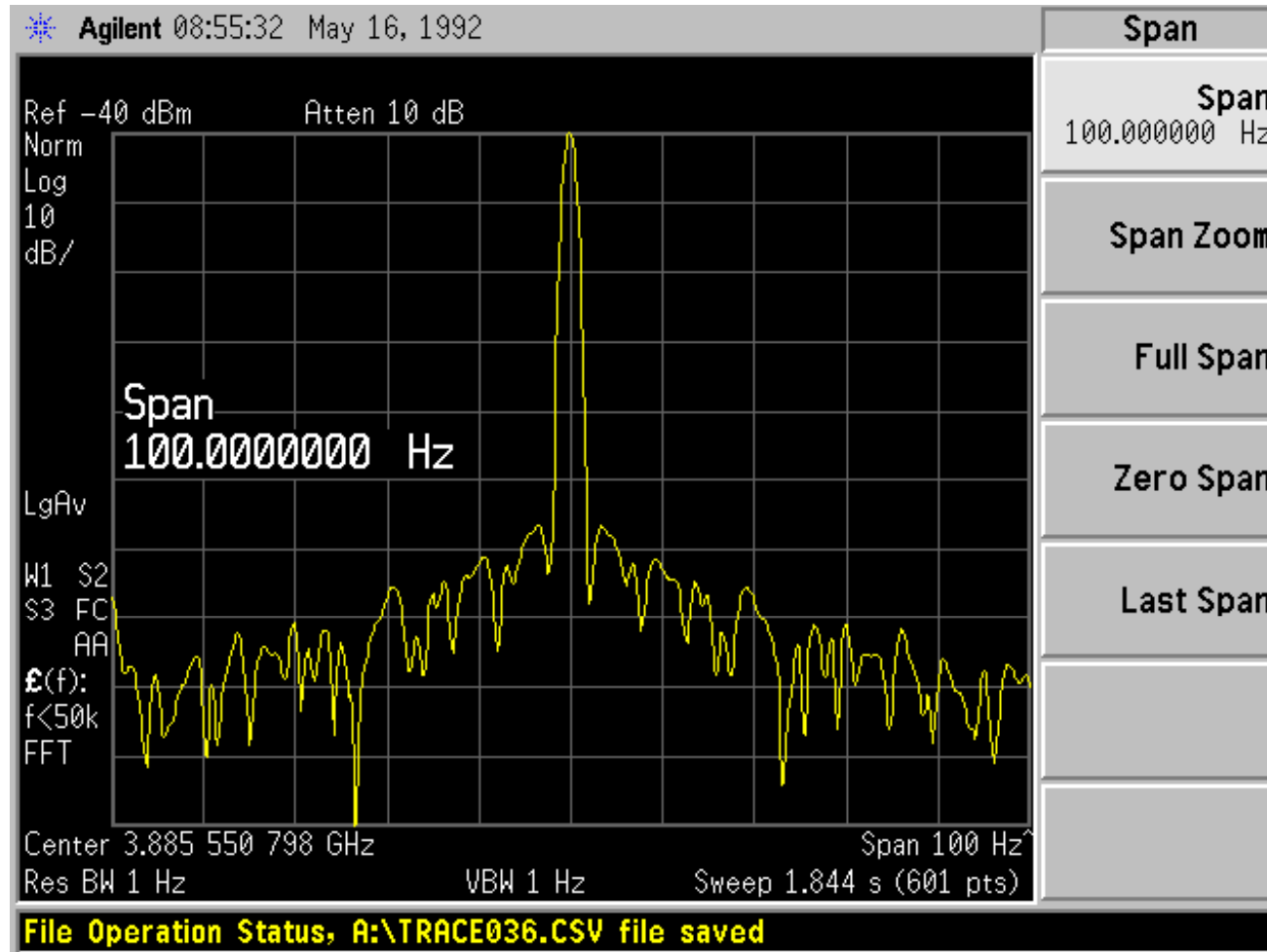
**Control boxes  
with  
interferometer  
components  
on top**

# Cavity 3 - unlocked



Max peak at -30dB corresponds to 2.5 degrees r.m.s. phase jitter at +/- 28 Hz

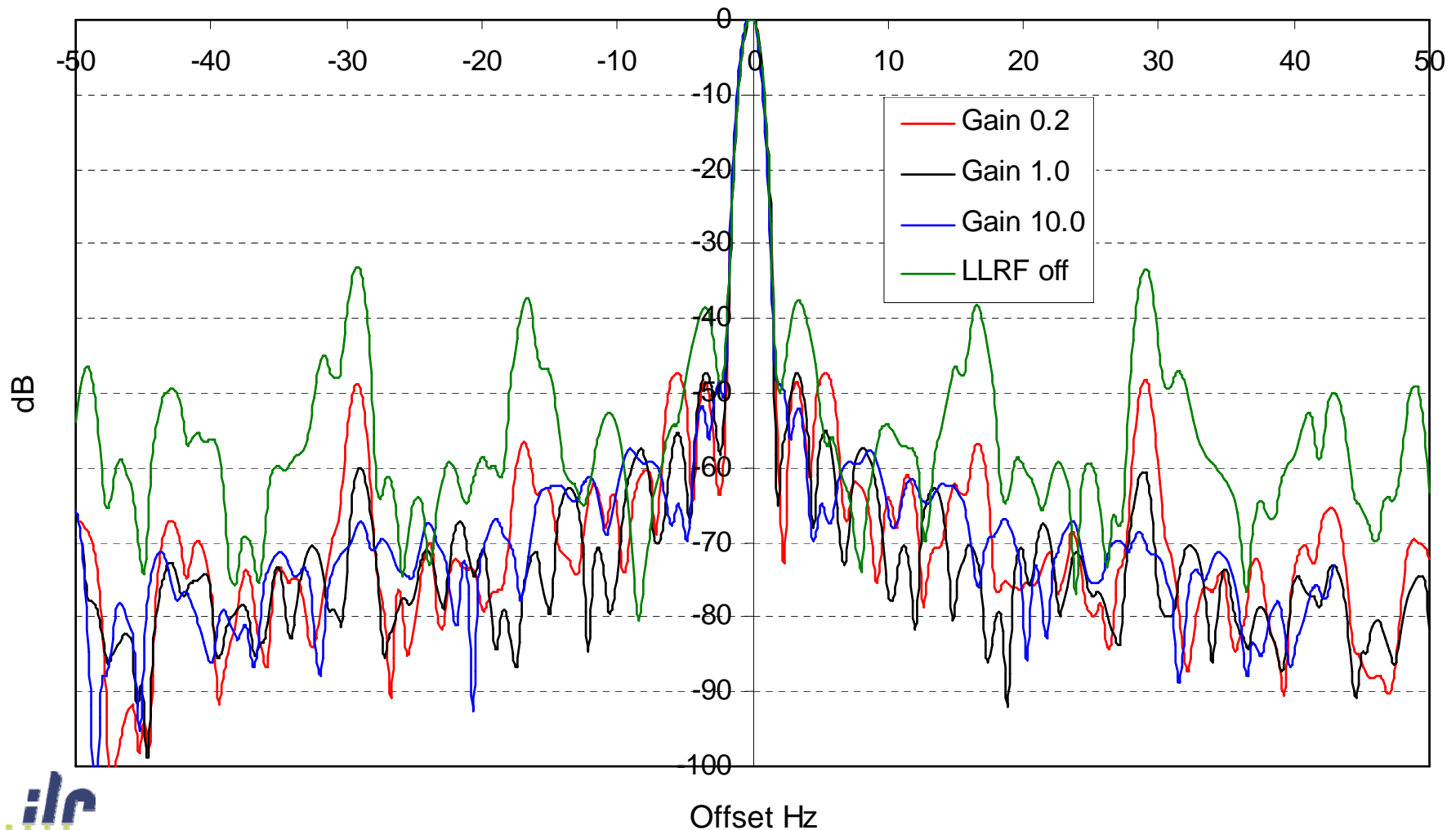
# Cavity 3 - Locked



at 10 Hz - 60dB  
corresponds to  
80 milli- degrees  
r.m.s. phase

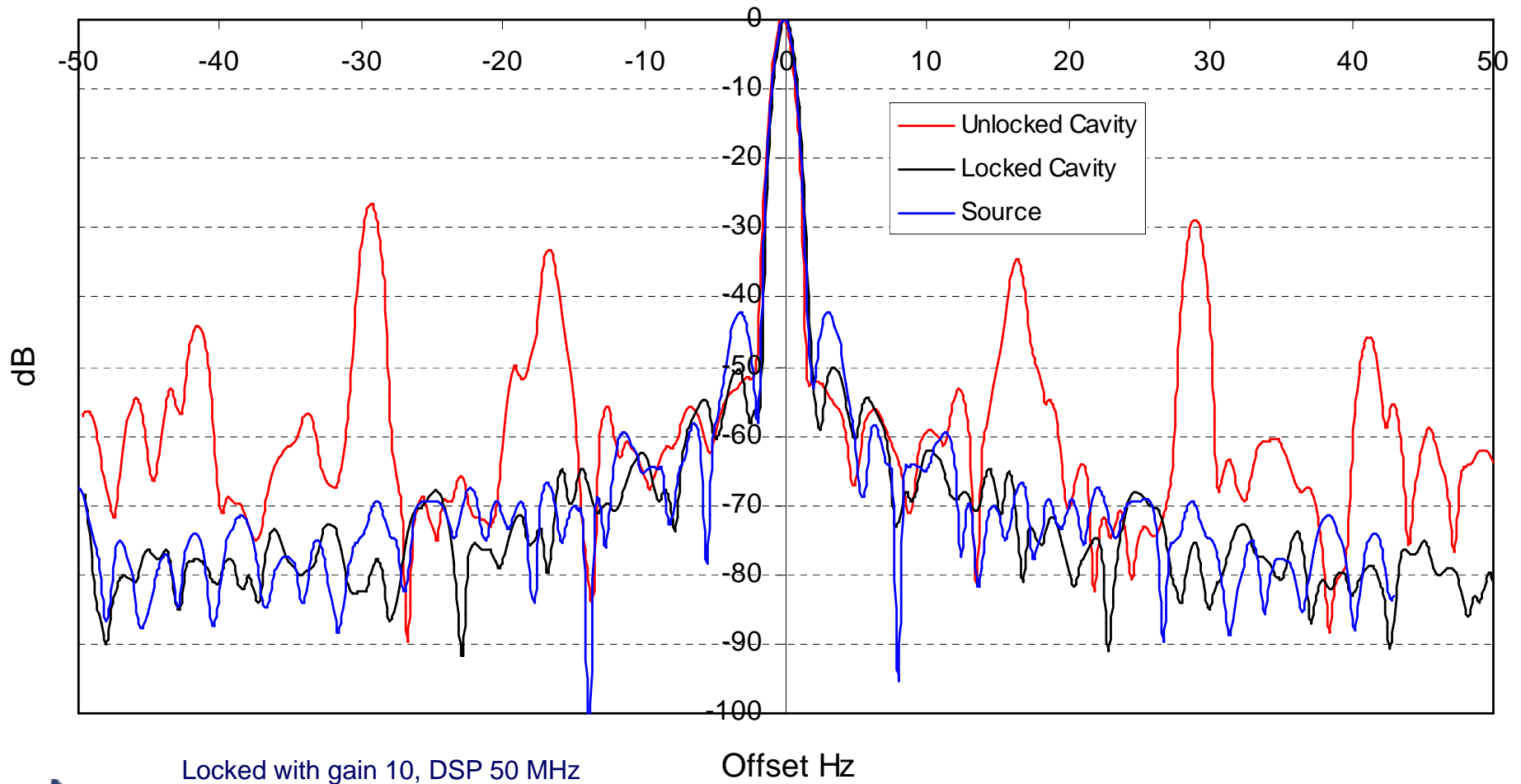
Close in noise  
comes from  
signal source

## *Locking Performance vs Gain with DSP Clock Speed of 50 MHz*





## *Source vs Output Spectrum for Cavity 3, Unlocked and Locked at High Gain*



## *Simultaneous Lock*

- Prior to locking DBM = 2V pk to pk
- With lock DBM = 50 mV pk to pk
- Prior to locking r.m.s jitter = 4 deg
- Achieved 100 milli-deg r.m.s.
- Target = 120 milli-deg r.m.s.

Precise calibration and optimisation of lock was difficult as cavity frequency drift prevented lock for significant periods of time.



*August 2008*

## *Absolute Calibration*

The phase detector boards are unlikely to offer identical path lengths at the level of 6  $\mu\text{m}$ . Differences can be calibrated out by bringing the boards together and placing a mixer across the coupler connection points. The interferometer would correct for changes in the cable length as the boards are taken back to their respective crab cavity systems.

This calibration process may not be that helpful as tolerances in the cavity and the couplers and their positioning is unlikely to place the centre of kick to better than some fraction of a millimetre.

**A beam based calibration system for initial set up needs to be devised.**



## *EuroTeV Deliverable*

Phase control tests have been undertaken

A EuroTeV a report is in preparation



## *Modelling Requirement*

Tests so far are

- For single cell
- In vertical cryostat
- Without beam

Hence validation at this stage also needs a model

**Modelling is complete and a EuroTeV Report is in preparation**



## *Cavity Phase Control Conclusion*

Phase stability performance has been modelled for

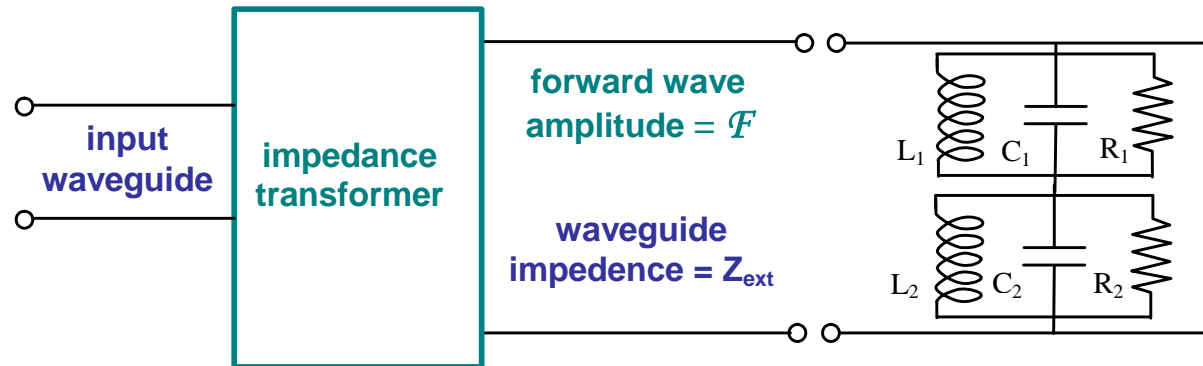
- anticipated beam jitter
- levels of microphonics observed in the FNAL CKM cavity
- measurement errors typical for digital phase detectors
- a target latency of  $1\mu\text{s}$
- Q external optimised for power transfer

RMS cavity phase jitter at optimum gain was 0.020 degrees

This is within the budget of 0.070 degrees.

# *Modelling Appendix*

# Phase Control Model



equivalent electrical circuit for excitation of two cavity modes

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

resulting differential equation for N modes

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

conversion from circuit parameters to cavity parameters

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

we need a numerical solution

## *Envelope Equations*

- Require an accurate solution over the cavity fill time plus the bunch train time
- At the design gradient the required energy per cell is 0.0284 J
- If 250 Watts per cell is available the minimum fill time ~ 0.12 ms
- For best possible phase performance we would want to fill slowly and let settle
- Allowing 4 ms for filling and operation simulation needs 20 million RF cycles
- We also plan a 10 ms settling time for Lorentz detuning effects after filling.

Instead of solving the full equations solve envelope equations for the in phase and quadrature components of the nominal frequency by setting

$$V_m(t) = \{ A_{rm}(t) + jA_{im}(t) \} \exp\{-j\omega t\}$$

and neglecting second derivatives of  $A_{rm}$  and  $A_{im}$  where m refers to the mode.

## *Hence Solve*

$$\dot{A}_{mr} = -\frac{\omega_m}{4Q_{om}} \left( \frac{\omega_m^2}{\omega^2} + 1 \right) A_{mr} - \frac{\omega_m}{4Q_{em}} \sum_{j=1}^N \left( \frac{\omega_j^2}{\omega^2} + 1 \right) A_{jr} + (\omega_m^2 - \omega^2) \frac{A_{mi}}{2\omega} - \frac{\omega_m}{\omega Q_{em}} (\dot{F}_i - \omega F_r)$$

$$\dot{A}_{mi} = -\frac{\omega_m}{4Q_{om}} \left( \frac{\omega_m^2}{\omega^2} + 1 \right) A_{mi} - \frac{\omega_m}{4Q_{em}} \sum_{j=1}^N \left( \frac{\omega_j^2}{\omega^2} + 1 \right) A_{ji} - (\omega_m^2 - \omega^2) \frac{A_{mr}}{2\omega} + \frac{\omega_m}{\omega Q_{em}} (\dot{F}_r + \omega F_i)$$

This form neglects order  $1/Q^2$

We have integrated the equations using 4<sup>th</sup> order Runge Kutta



## *With Beamloading*

Beamloading is included in the model with incremental changes of field amplitudes when the bunches pass through determined using

$$A_r(\text{final}) = A_r(\text{initial}) + \frac{r_b \omega}{c} \omega \left( \frac{R}{Q} \right)'_{\text{FNAL}} q \cos \alpha$$

$$A_i(\text{final}) = A_i(\text{initial}) + \frac{r_b \omega}{c} \omega \left( \frac{R}{Q} \right)'_{\text{FNAL}} q \sin \alpha$$

Where  $\alpha$  is the phase of a bunch,  $q$  is its charge,  $r_b$  is its offset, All these parameter could vary from bunch to bunch. Each mode is affected in proportion to is  $(R/Q)$



# The Controller

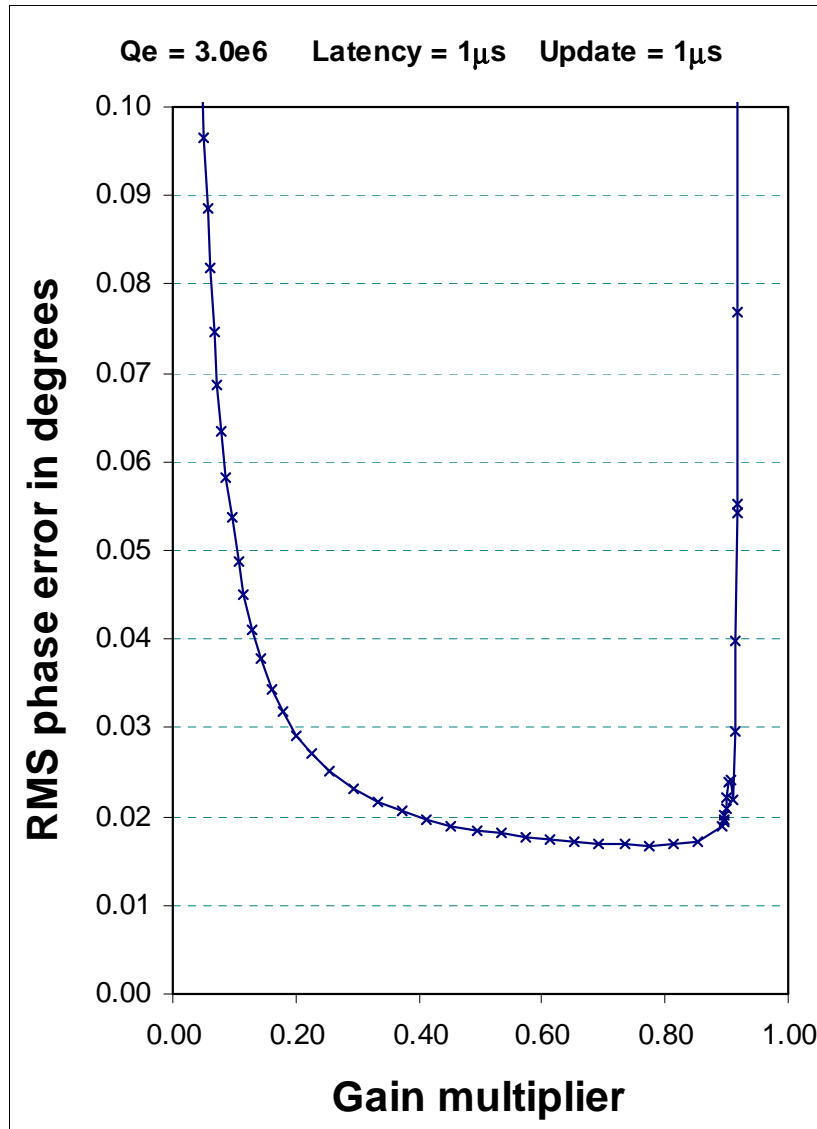
The simplest controller for a system with random disturbance such as off axis bunches and where state measurement is noisy is a Proportional Integral controller. Our simulations use a PI controller throughout. When the real system has been characterised alternative controllers may perform better. The forward power  $\mathcal{F}$  which corrects the I and Q cavity amplitudes  $A$  is inescapably delayed by the control system by time  $t_{\text{delay}}$

$$\mathcal{F}_r(t + t_{\text{delay}}) = c_{\text{pr}} (V_{\text{sp}} - A_{1r}) + c_{\text{ir}} \int_{-\infty}^t dt (V_{\text{sp}} - A_{1r})$$
$$\mathcal{F}_i(t + t_{\text{delay}}) = -c_{\text{pi}} A_{1i} - c_{\text{ii}} \int_{-\infty}^t dt A_{1i}$$

Ideally one measures the amplitude and phase of the operating mode to give  $A_{1r}$  and  $A_{1i}$ . In reality one samples all the adjacent modes at the same time unless the input filter is very clever or very slow. The model assumes all adjacent modes are sampled.



# Performance verses gain



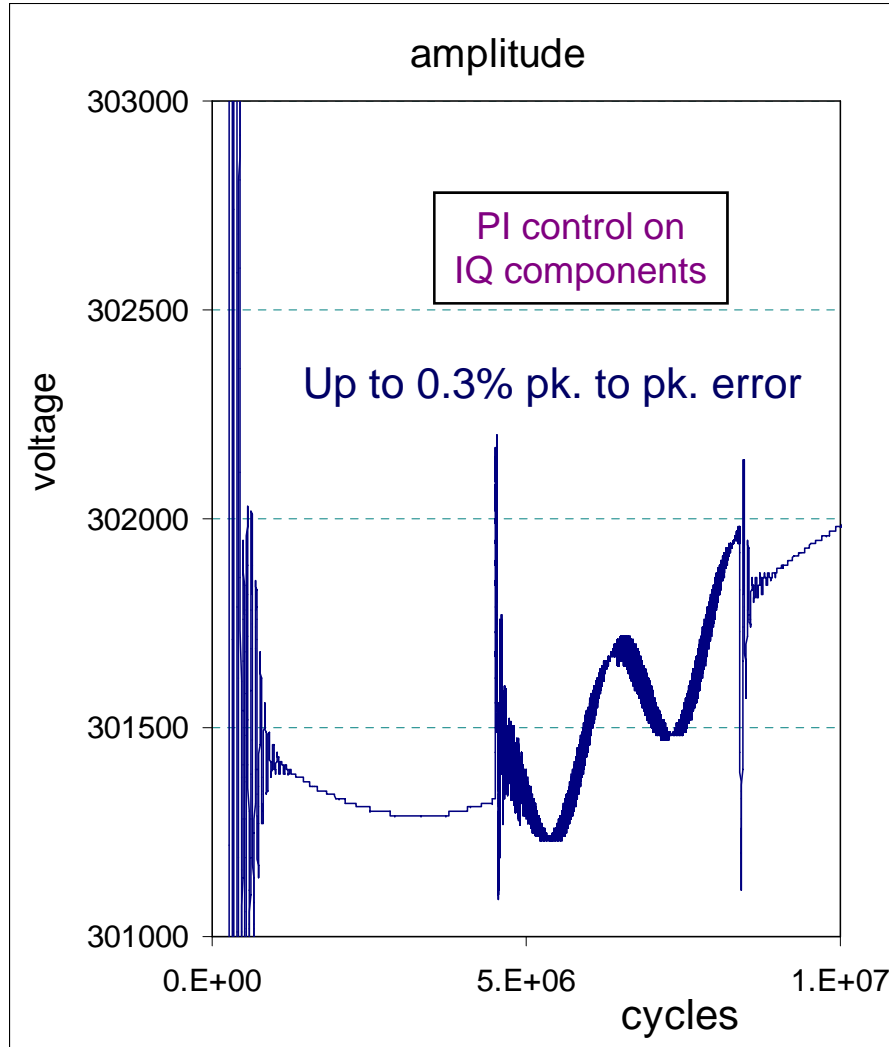
Drive frequency in GHz	=	3.900 GHz
Centre cavity frequency in GHz	=	3.900 GHz
Number of cavity modes	=	3
Cavity Q factor	=	1.0E+09
External Q factor	=	3.0E+06
Cavity R over Q (2xFNAL=53 per cell)	=	53.0 ohms
Energy point ILC crab~0.0284J per cell)	=	28.4 mJ
Amplitude set point	=	301.675 kV
Maximum Amplifier Power per cell	=	1200 W
Maximum voltage set point (no beam)	=	1235.476 kV
Maximum beam offset	=	0.6 mm
Maximum bunch phase jitter	=	1.0 deg
Beam offset frequency	=	2000 Hz
Bunch charge (ILC=3.2 nC)	=	3.2 nC
RF cycles between bunches	=	1200.0
Bunch train length	=	1.0 ms
Cavity frequency shift from microphonics	=	600.0 Hz
Cavity vibration frequency	=	230.0 Hz
Initial vibration phase (degrees)	=	20.0 deg
Phase measurement error(degrees)	=	0 deg
Fractional err in amplitude measurement	=	0
Time delay (latency) for control system	=	1.0E-06 s
Control update interval	=	1.0E-06 s
Initial gain constant for controller	=	0.005
Amplifier bandwidth	=	1.0E+07
Measurement filter bandwidth	=	5.0E+05
Optimal gain constant for controller	=	0.7734
Minimum rms phase error	=	0.01679
Maximum power delivered	=	167.3547
Proportional coef for real component	=	4.6403E+01
Integral coef for real component	=	- 1.3921E-03
Proportional coef for imag component	=	4.6403E+01
Integral coef for imag component	=	1.3921E-03



# Amplitude Control



Bunch train introduced after 4.5e5 cycles with 0.6 mm oscillating offset.  
No measurement errors included in this calculation (see later for measurement errors).

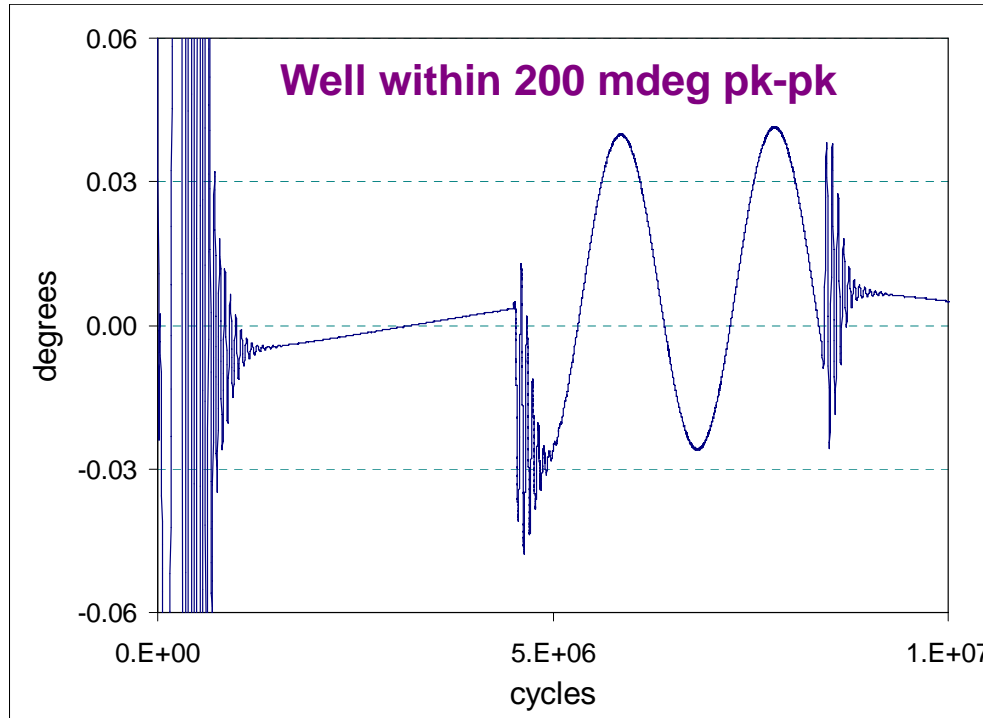


Drive frequency in GHz	=	3.900 GHz
Centre cavity frequency in GHz	=	3.900 GHz
Number of cavity modes	=	3
Cavity Q factor	=	1.0E+09
External Q factor	=	3.0E+06
Cavity R over Q (2xFNAL=53 per cell)	=	53.0 ohms
Energy point ILC crab-0.0284J per cell)	=	28.400 mJ
Amplitude set point	=	301.675 kV
Maximum Amplifier Power per cell	=	1200.000 W
Maximum voltage set point (no beam)	=	1235.476 kV
Maximum beam offset	=	0.6 mm
Maximum bunch phase jitter	=	1.0 deg
Beam offset frequency	=	2000.0 Hz
Bunch charge (ILC=3.2 nC)	=	3.2 nC
RF cycles between bunches	=	1200.0
Bunch train length	=	1.0 ms
Cavity frequency shift from microphonics	=	600 Hz
Cavity vibration frequency	=	230 Hz
Initial vibration phase (degrees)	=	20 deg
Phase measurement error(degrees)	=	0 deg
Fractional err in amplitude measurement	=	0
Time delay (latency) for control system	=	1.0E-06 s
Control update interval	=	1.0E-06 s
Gain constant for controller	=	0.7
Amplifier bandwidth	=	1.0E+07
maximum power delivered	=	167.34
In pulse rms phase err	=	0.02560 degrees
In pulse rms amplitude err	=	0.07966 %
Relative excitation of 2nd mode	=	0.03260 %
Relative excitation of 3rd mode	=	0.01756 %

Proportional coef for real component	=	4.20E+01
Integral coef for real component	=	1.26E-03
Proportional coef for imag component	=	4.20E+01
Integral coef for imag component	=	1.26E-03



# Phase Control



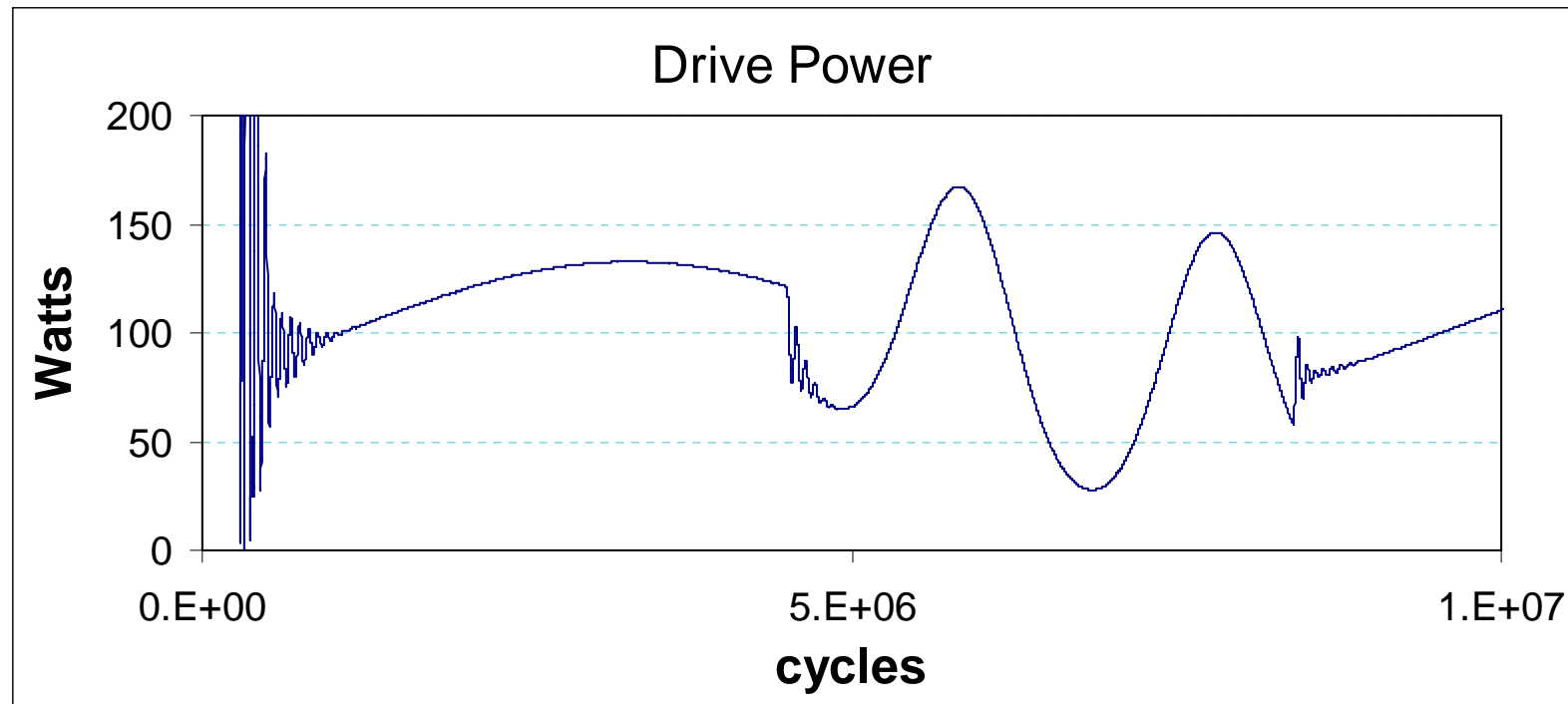
- No measurement errors included
- Three modes included ( $\pi$  ,  $8\pi/9$  ,  $7\pi/9$ )
- 0.6 mm oscillating beam offset
- 712 fs random, bunch timing errors
- Control loop latency  $\sim 1 \mu\text{s}$  (expect to achieve)
- Fast oscillation follows beamload (0.6 mm oscil.)
- Slow oscillation follows microphonics
- Gain backed off by 30% from stability limit

Drive frequency in GHz	=	3.9 GHz
Centre cavity frequency in GHz	=	3.9 GHz
Number of cavity modes	=	3
Cavity Q factor	=	1.0E+09
External Q factor	=	3.0E+06
Cavity R over Q (2xFNAL=53 per cell)	=	53.0 ohms
Energy point ILC crab~0.0284J per cell)	=	28.4 mJ
Amplitude set point	=	301.675 kV
Maximum Amplifier Power per cell	=	1200 W
Maximum voltage set point (no beam)	=	1235.476 kV
Maximum beam offset	=	0.6 mm
Maximum bunch phase jitter	=	1.0 deg
Beam offset frequency	=	2000 Hz
Bunch charge (ILC=3.2 nC)	=	3.2 nC
RF cycles between bunches	=	1200
Bunch train length	=	1.0 ms
Cavity frequency shift from microphonics	=	600 Hz
Cavity vibration frequency	=	230 Hz
Initial vibration phase (degrees)	=	20 deg
Phase measurement error(degrees)	=	0 deg
Fractional err in amplitude measurement	=	0
Time delay (latency) for control system	=	1.0E-06 s
Control update interval	=	1.0E-06 s
Gain constant for controller	=	0.7
Amplifier bandwidth	=	1.0E+07
Measurement filter bandwidth	=	5.0E+05
maximum power delivered	=	167.34
In pulse rms phase err	=	0.02560 deg
In pulse rms amplitude err	=	0.07966 %
Relative excitation of 2nd mode	=	0.03260 %
Relative excitation of 3rd mode	=	0.01756 %

Proportional coef for real component	=	4.2000E+01
Integral coef for real component	=	1.2600E-03
Proportional coef for imag component	=	4.2000E+01
Integral coef for imag component	=	1.2600E-03



## *Power requirement per cell*

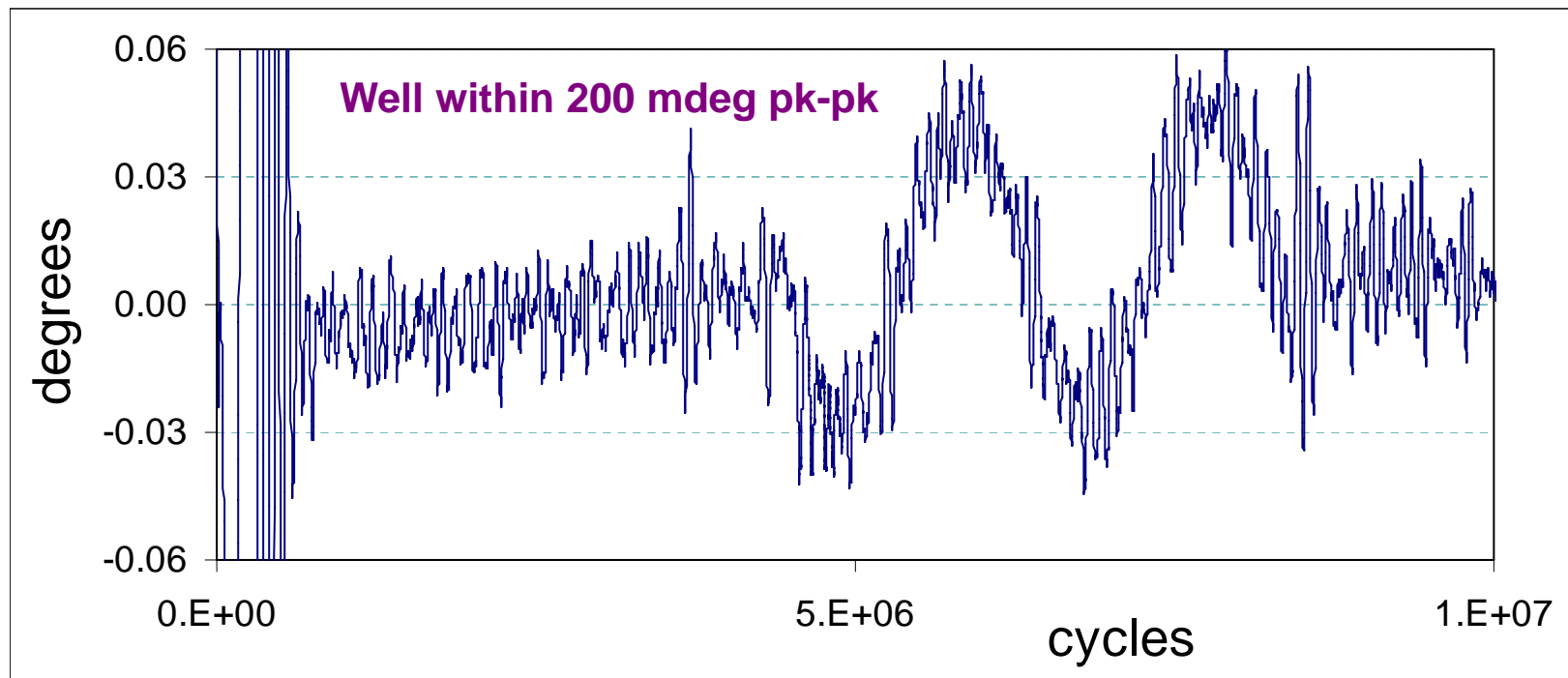


- During this pulse a nine cell cavity needs 1.5 kW peak power.
- Worst case peak power here ~ 220 Watts per cell i.e. 2 kW
- This means that power supply ripple and hence amplifier jitter will not be a big issue.
- Solid State amplifiers are an option.



## *Phase control with measurement error*

Parameters as before but gain backed off by 20%  
with random phase measurement error of  $\pm 0.020$  degrees  
and random amplitude measurement error of  $\pm 0.1\%$   
measurement signal filter = 500 kHz

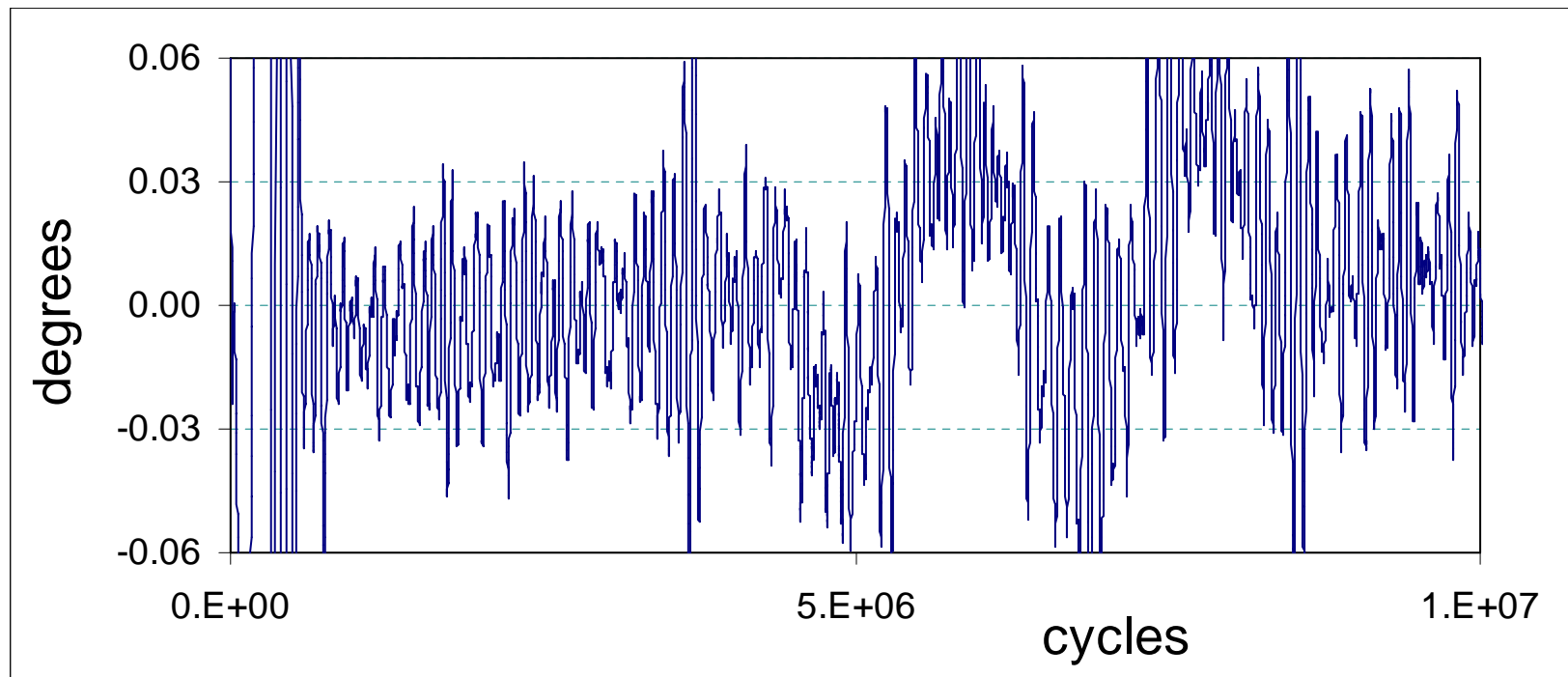


Modelling indicates that for a system latency of  $1\ \mu\text{s}$  the phase performance is limited by ones ability to estimate excitation of the operating mode in the presence of other partly excited modes.



## *Phase control with increase amplitude error*

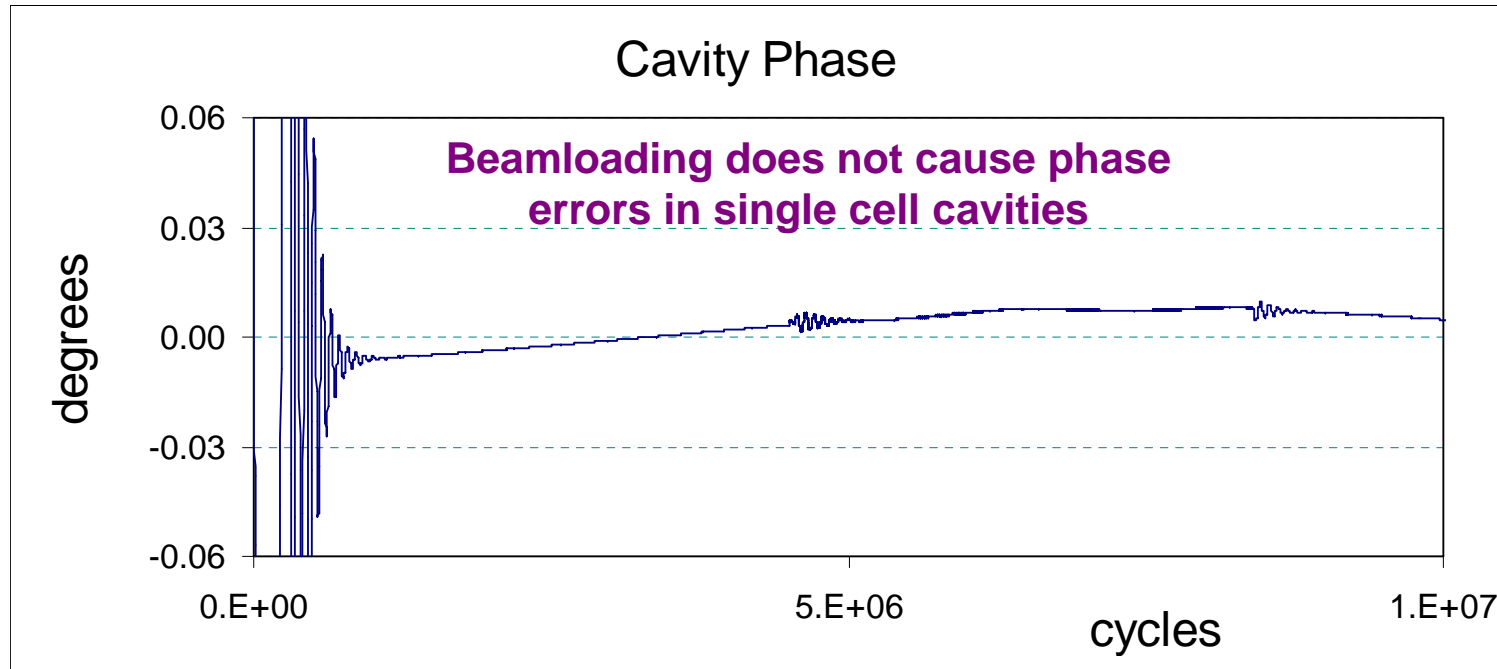
Parameters as before  
with random phase measurement error of  $\pm 0.020$  degrees  
and random amplitude measurement error of  $\pm 0.3\%$   
measurement signal filter = 500 kHz



Poor accuracy in measuring amplitude  
affects one ability to control the phase



# Phase Control for Single Mode Cavity



- No measurement errors included
- Only  $\pi$  mode included
- 0.6 mm oscillating beam offset
- 712 fs random, bunch timing errors
- Control loop latency  $\sim 1 \mu\text{s}$
- Fast oscillation following beamload (0.6 mm oscil.) is removed
- Slow oscillation follows microphonics



# Performance verses gain with measurement errors

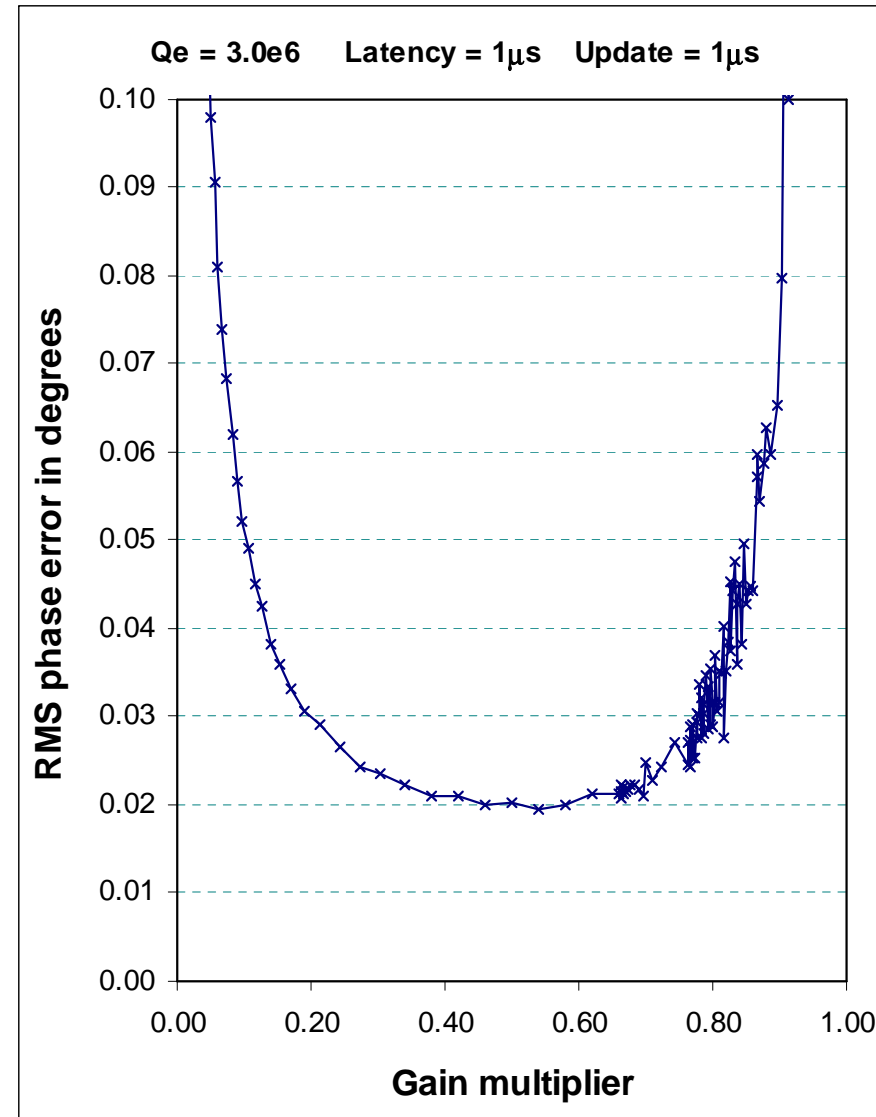
PARAMETERS NOT LISTED ARE AS BEFORE

Phase measurement error (degrees)	=	0.015 deg
Fractional err in amplitude measurement	=	0.001
Optimal gain constant for controller	=	0.5406
Minimum rms phase error	=	0.01965
Maximum power delivered	=	189.9387
Proportional coef for real component	=	3.2437E+01
Integral coef for real component	=	9.7312E-04
Proportional coef for imag component	=	3.2437E+01
Integral coef for imag component	=	9.7312E-04

The phase stability limit depends on latency and external Q factor.

For analytic calculations see for instance

**Elmar Vogel "High Gain Proportional RF control stability at TESLA cavities, Physical Review Special Topics – Accelerators and Beams vol 10 (2007)**





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## *Control system upgrades for consideration*

1. Operation of the interferometer at 3.9 GHz
2. Use of double balanced mixers alongside the digital phase detectors
3. Use of an optical interferometer.



## *Planned development tasks*

1. Continue development of monolithic phase detector board.
2. Interface FPGA to DSP on cavity control board.
3. Replace analog. loop filter on interferometer with FPGA controllers.
4. Develop automatic calibration of interferometer.
5. Develop interface with cavity tuners.
6. More performance test on pairs of superconducting cavities at 1.3 GHz and 3.9 GHz.
7. Investigate the applicability of advanced control algorithms beyond PI.
8. Develop RF controller for active damping of the SOM.