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Low Level RF for Crab Cavities (The ILC in particular)

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ILC Crab Cavity Collaboration

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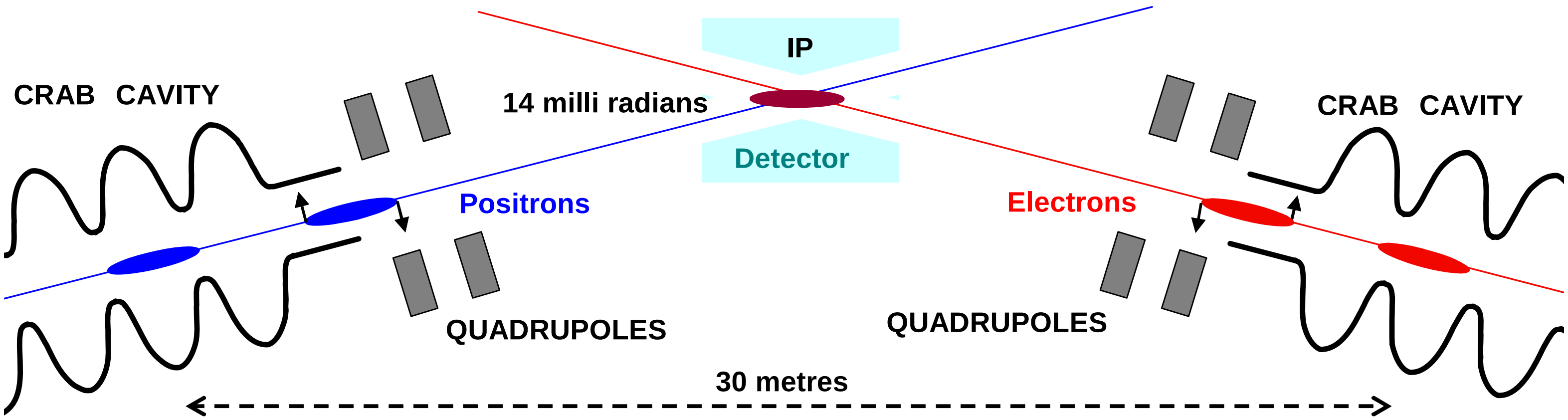
ILC Layout



- Phase error in the crab cavity systems causes unwanted kicks.
- Differential phase errors between the systems causes bunches to miss each other.
- Crab cavity zero crossings need synchronisation to 90 fs for the 2% luminosity loss budget (for $\sigma_x = 0.655\ \mu m$, $\sigma_z = 0.3$ mm at 500GeV).
- One degree r.m.s. crab system to system phase error reduces luminosity by 37%.
- Not using crab cavities reduces luminosity by $$\left\{1+\left(\frac{\sigma_z\theta_c}{2\sigma_x}\right)^2\right\}^{-0.5} = 80\%$$

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Technology Selection

The decision to pursue a superconducting cavity solution was made as

1. a copper cavity would need a power input in the range 200kW - 2MW depending on frequency, hence Klystron jitter and coupler expansion would become key issues with respect to achieving the required phase stability. Proof that the phase control tolerance could be met would be difficult until a system operating at full power had been tested. (For instance a 6µm expansion of the coupler might be a problem).

2. Phase stabilisation has been demonstrated of a 1.3 GHz s.c. cavity (Qext=2e7) to 0.02 degrees rms using a Cornell digital control system at the JLab IR-FEL (Liepe et al.). This corresponds to a synchronisation of 42 fs.

Frequency selection

The decision to work on a 3.9 GHz s.c. cavity rather than a 1.3 GHz or a 2.6 GHz cavity was made because

1. it took up the least space longitudinally and transversely
2. it required the least power
3. FNAL were already working on an appropriate cavity.

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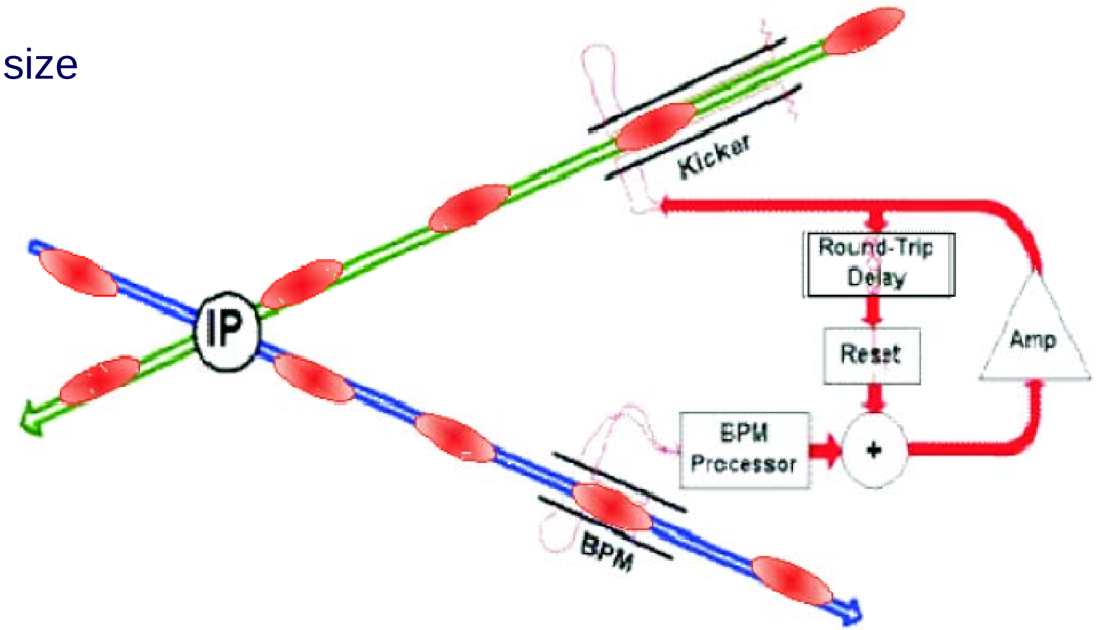
Equations for Linear Collider Crab Correction

		ILC
Relation between displacement at ip and transverse kick at the crab cavity	$x_{ip} = R_{12} x'_c = \sqrt{\beta_{ip}} \sqrt{\beta_{crab} - \beta_o}\ x'_c$	R_{12} = 16.3 m
Kick depends on relative time of arrival t (note voltage kick defined from eV=pc)	$x'_c = \frac{\Delta p}{mc} = \frac{V_{max}}{E_o} \sin(\omega t)$	$\omega / 2\pi$ = 3.9 GHz
Displacement for late arrival at time t where $\theta_r = 0.5\ \theta_c$	$\Delta x_{ip} = R_{12} \frac{V_{max}}{E_o} \sin(\omega t) \cong \theta_r c t$	E_o = 250 GeV
Kick voltage V_{max} required from system to achieve a rotation angle of θ_r is given by	$\theta_r = \frac{\Delta x_{ip}}{\sigma_z} \cong R_{12} \frac{V_{max}}{E_o} \frac{\omega}{c}$	V_{maz} = 1.32 MV
Luminosity reduction factor due to relative offset at IP	$S = \exp\left(-\frac{\Delta x^2}{4\sigma_x^2} \right)$	$\Delta x\,(max)$ = 186 nm For σ_x = 655 nm

Bunch Alignment

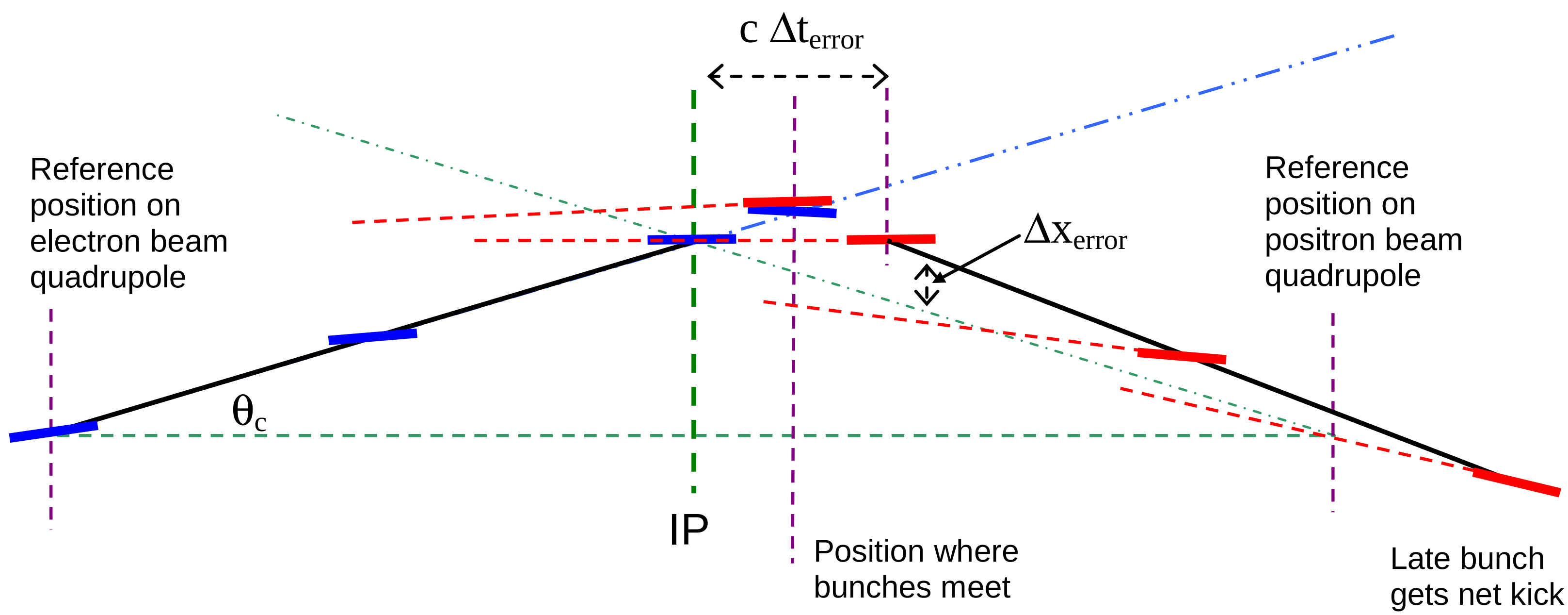
Nominal ILC bunch size
for 500 GeV c.o.m.
$\sigma_z = 300\ \mu m$,
$\sigma_x = 0.655\ \mu m$,
$\sigma_y = 0.004\ \mu m$



A Horizontal version of FONT has been proposed by Phil Burrows (Oxford) and Chris Adolphson (SLAC), but is apparently more difficult than the vertical FONT system they have already developed.

Horizontal alignment may need to rely on dipole correctors positioned before the crab cavity. In principle unwanted kicks by the crab cavities can be corrected if they are slowly varying in time. When the crab cavities are energised there must be sufficient luminosity for a horizontal font system, if used to take control.

Case for Synchronisation



Loss of luminosity from vertical defocusing, timing error on the bunch arrival to 500 fs

Without the effect of vertical defocusing the beam to crab cavity error when the crab cavities are synchronised can be 9600 fs (~ 13.5º at 3.9 GHz) before luminosity loss exceeds 2%

The alternative to synchronisation is to run both cavities independently from very stable oscillators that phased to the bunches and use dipole correctors to remove the offset.

Synchronisation Requirements

Linac timing requirement is nominally 0.1 degrees at 1.3 GHz ~ 200 fs and hence cannot be relied upon to provided 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.

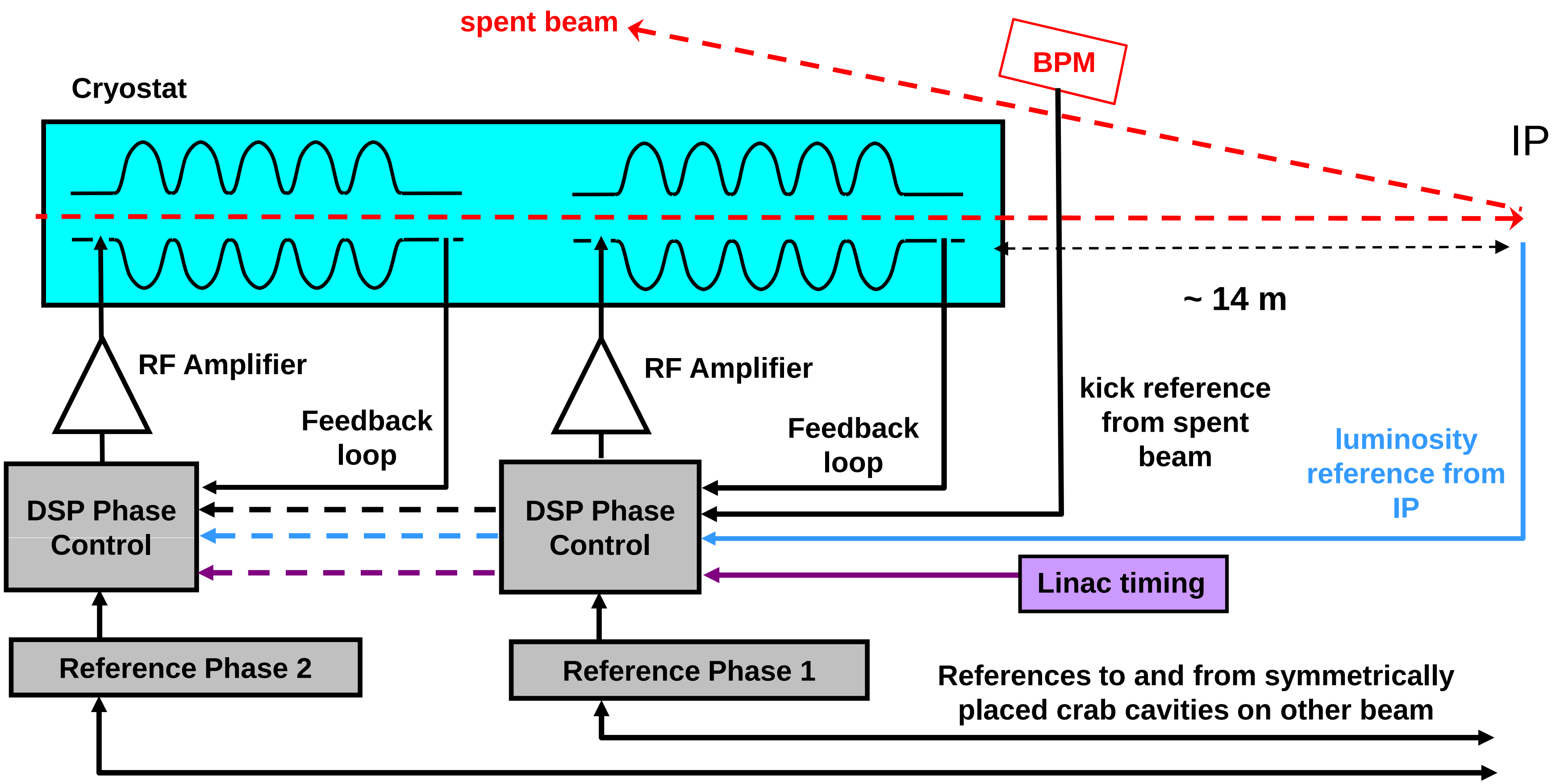
Proposed Scheme

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.

Anticipated RF system



Minimum requirement for 14 mrad crossing is 1×9 cell or 2×5 - cell cavities per linac 2×9 – cells would provide full redundancy in case of failure

Need space for cryostat, input/output couplers, tuning mechanisms…

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Synchronisation Timing

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

The timing budget might be considered as three equal uncorrelated parts give as 90 fs / √3 =51 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 (~ 1°C) gives a timing shift of 167 fs.
- 20 fs corresponds to 6 μm hence if the synchronisation is to be by dead reckoning then 6 μm 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.

Constant offset to r.m.s. conversion

Luminosity reduction factor $S_{rms} \approx S$ follows from

$$S(\phi) = \exp\left\{-\left(\frac{c\,\theta_r\,\phi}{2\,\sigma_x\,\omega}\right)^2\right\}$$

$$S_{rms}(\phi_{rms}) = \left(1+\left(\frac{c\,\theta_r\phi_{rms}}{\sigma_x\omega}\right)^2\right)^{-\frac{1}{4}}$$

	250 GeV beam (nominal)		500 GeV beam (nominal)		500 GeV beam (low Q)	
sigma x	6.55E-07	**6.55E-07**	5.54E-07	5.54E-07	3.92E-07	3.92E-07
half crab crossing (rad)	0.010	**0.007**	0.010	0.007	0.010	0.007
frequency	3.90E+09	**3.90E+09**	3.90E+09	3.90E+09	3.90E+09	3.90E+09
luminosity reduction S	0.9800	**0.9800**	0.9800	0.9800	0.9800	0.9800
phase error rms (deg)	0.0890	**0.1271**	0.0753	0.1075	0.0533	0.0761
const. phase error (deg)	0.0872	**0.1246**	0.0738	0.1054	0.0522	0.0746
phase err rms (ps)	0.0634	**0.0905**	0.0536	0.0766	0.0379	0.0542
phase err pk to pk (deg)	0.2466	**0.3523**	0.2086	0.2980	0.1476	0.2109

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 expect phase control to this level at this frequency to be possible for a crab cavity where the level of disturbance is low.
- Low Level RF circuits can make measurements at the milli-degree level.
- For the digital phase detectors we are currently using we have measured pk–pk noise of 20 mdeg for a bandwidth of 1 MHz at 1.3 GHz hence when used with a divider we have 60 mdeg pk-pk noise for measurements at 3.9 GHz

Amplitude Stability Requirement

From consideration of incorrect rotation only

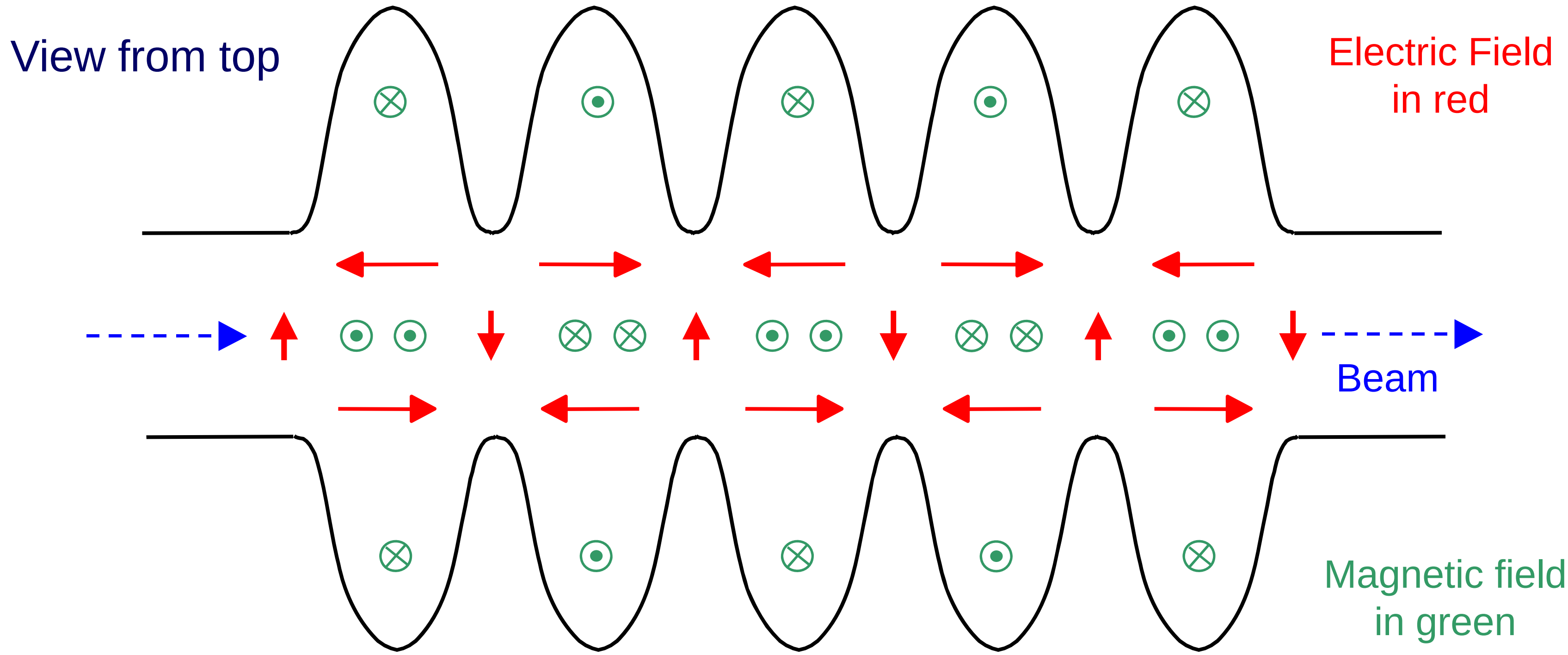
$$\frac{\Delta V}{V_{max}} \approx \frac{1}{\theta_r}\frac{\sigma_x}{\sigma_z}\sqrt{\frac{1}{S^2}-1} = \frac{0.655}{0.007\times 300}\sqrt{\frac{1}{0.98^2}-1} \quad = \quad 4.4\%$$

However poor control of amplitude affects one ability to measure and control the phase

ILC RDR parameters assuming use of FNAL CKM cavity

Crossing angle	14 mrad
Cavity frequency, GHz	3.9 GHz
Kick required at 0.5 GeV CM	1.32 MV
Anticipated operational gradient at 0.5 GeV CM	3.81 MV m^{-1}
Max gradient achieved in 3 cell cavity MV m^{-1}	7.5 MV m^{-1}
RMS relative phase stability for 2% rms Luminosity drop	0.13°
Cavity amplitude tolerance for 2% rms Luminosity drop	4.4%
Potential X beam jitter at crab cavity, µm	500 µm
Potential Y beam jitter at crab cavity, µm	35 µm

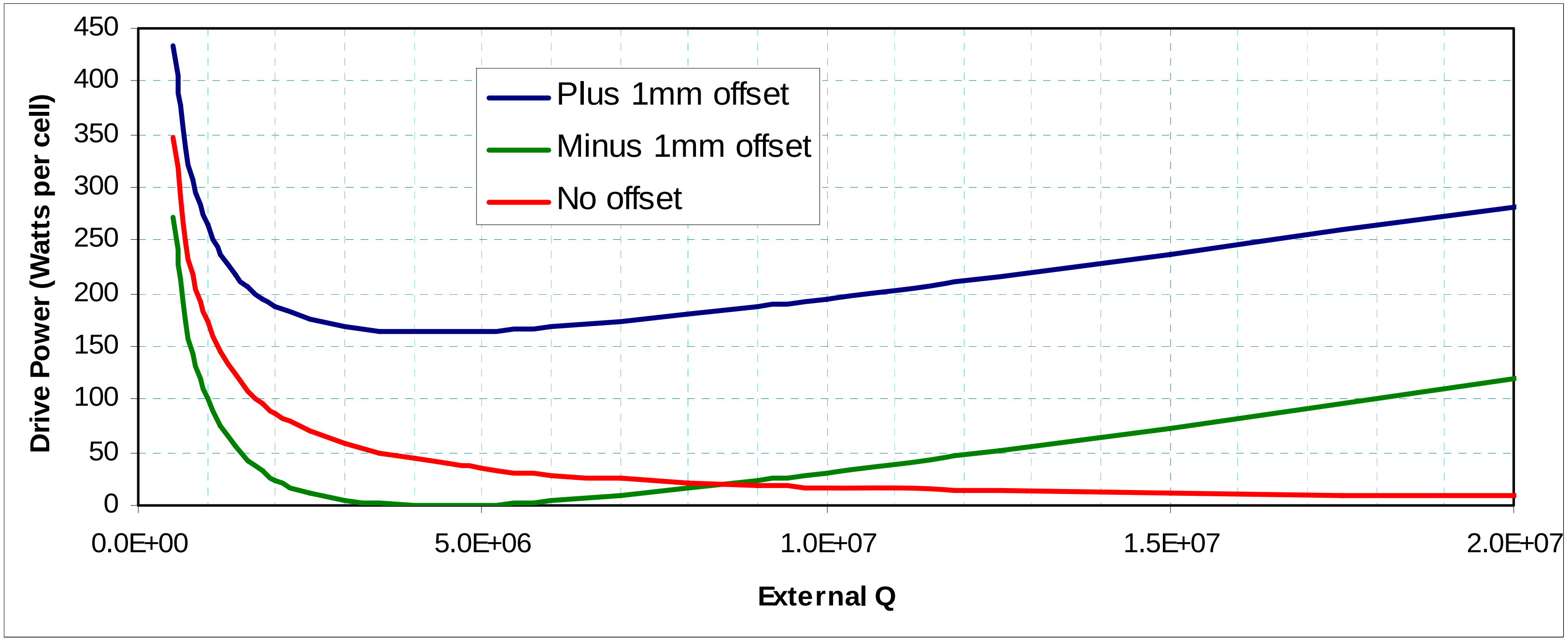
Multi-Cell Field Distribution



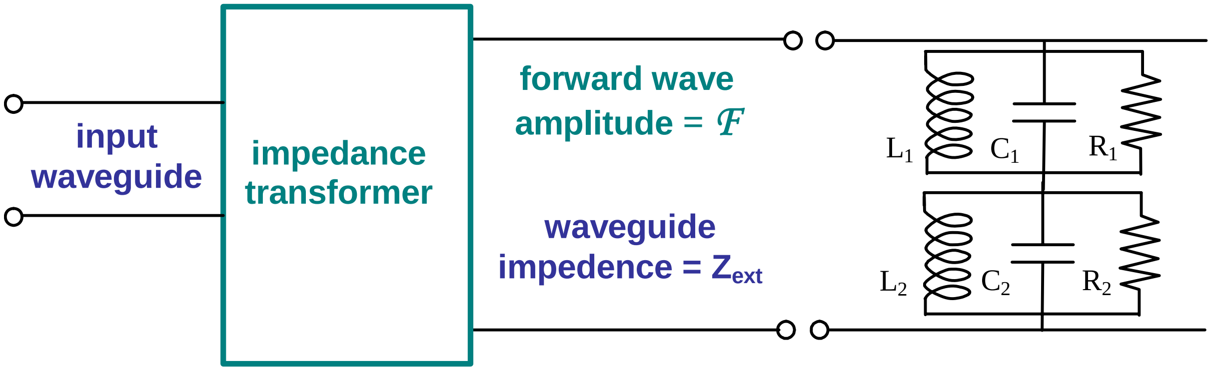
The electric and magnetic fields are 90º out of phase.
For a crab cavity the bunch centre is at the cell centre when E is max and B is zero.
A particle at the centre of the bunch sees no electric or magnetic field throughout .
Near equal kick from electric and magnetic field for CKM shape

Beamloading

- Longitudinal electric field on axis is zero for the dipole mode
- Beamloading loading is zero for on axis bunches
- Bunches pass cavity centre when B transverse = 0 hence off axis E = maximum
- Crab cavities are loaded by off axis bunches
- Dipole deflection cavities are not loaded by off axis bunches
- Power requirement for 9 cells (500 GeV CoM) ~ a few kW
- Adding an allowance for loading from microphonics suggests an external Q of 3e6



Phase Control Model



equivalent electrical circuit for excitation of two cavity modes

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

resulting differential equation for N modes

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

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, the coupler temperature

we need a numerical solution

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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

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

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

Hence Solve

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

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

This form neglects order $1/Q^2$

We have integrated the equations using 4th 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 α 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_{delay}

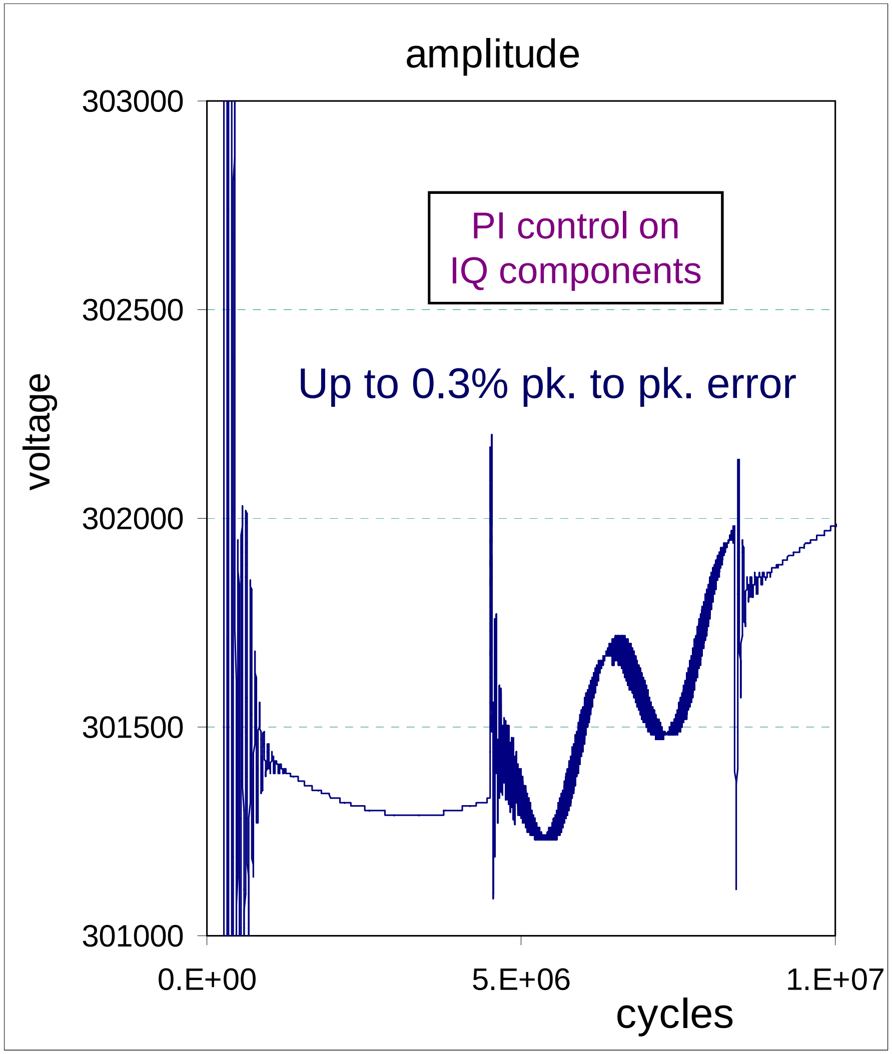
$$\mathcal{F}_r\left(t + t_{delay}\right) = c_{pr}\left(V_{sp} - A_{1r}\right) + c_{ir}\int_{-\infty}^{t} dt\,\left(V_{sp} - A_{1r}\right)$$

$$\mathcal{F}_i\left(t + t_{delay}\right) = -c_{pi}\,A_{1i} - c_{ii}\int_{-\infty}^{t} dt\,A_{1i}$$

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.

Amplitude Control

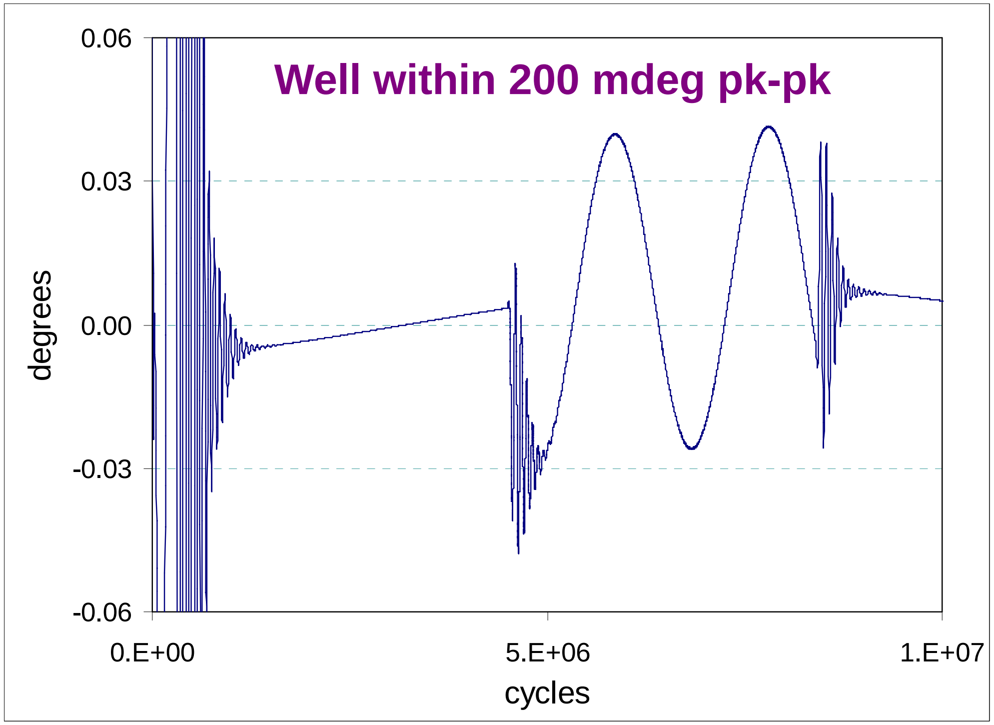
Bunch train introduced after 4.5e5 cycles with 0.6 mm oscillating offset.
No measurement errors included in this calculation (see later for measurement errors).



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

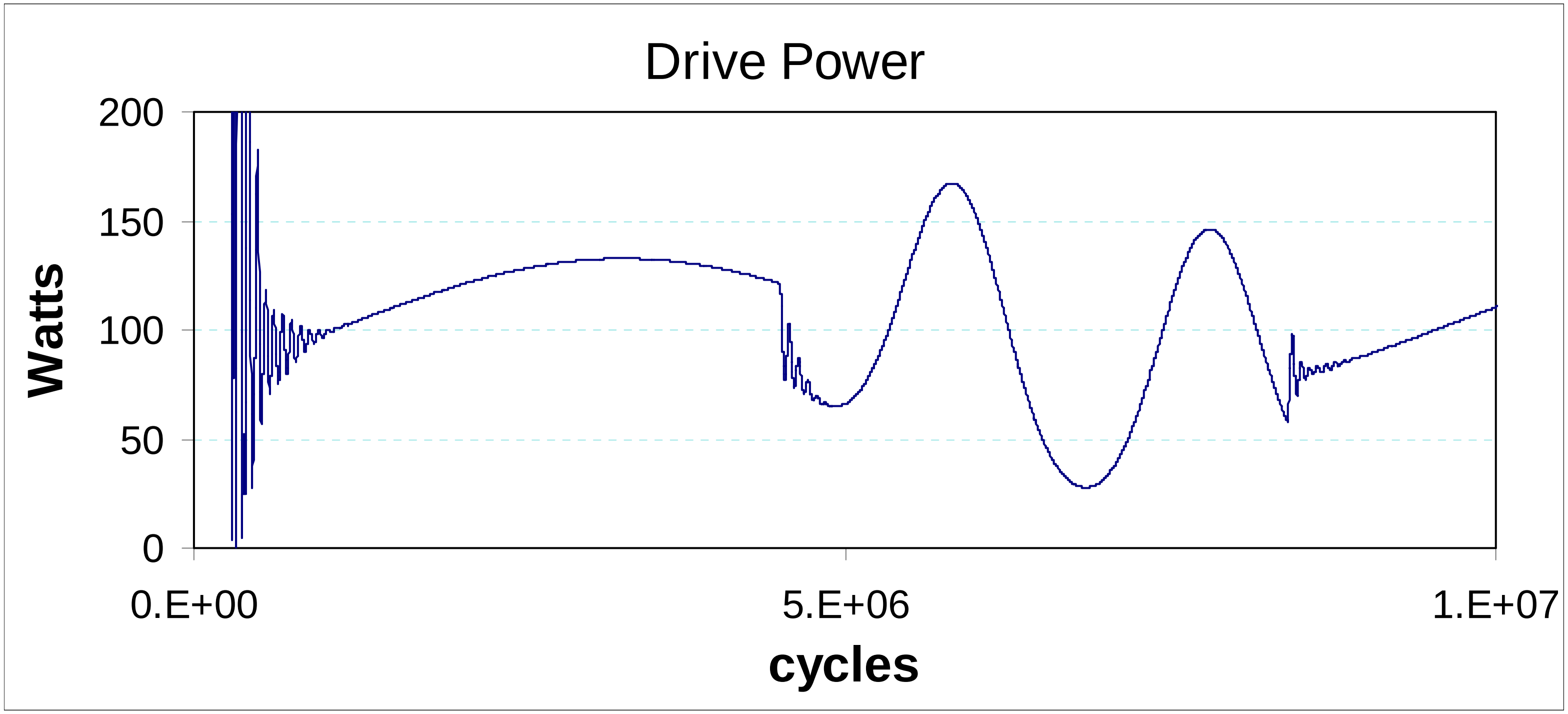


- No measurement errors included
- Three modes included (π , 8π/9 , 7π/9)
- 0.6 mm oscillating beam offset
- 712 fs random, bunch timing errors
- Control loop latency ~ 1 μs (expect to achieve)
- Fast oscillation follows beamload (0.6 mm oscil.)
- Slow oscillation follows microphonics
- Gain backed off 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.

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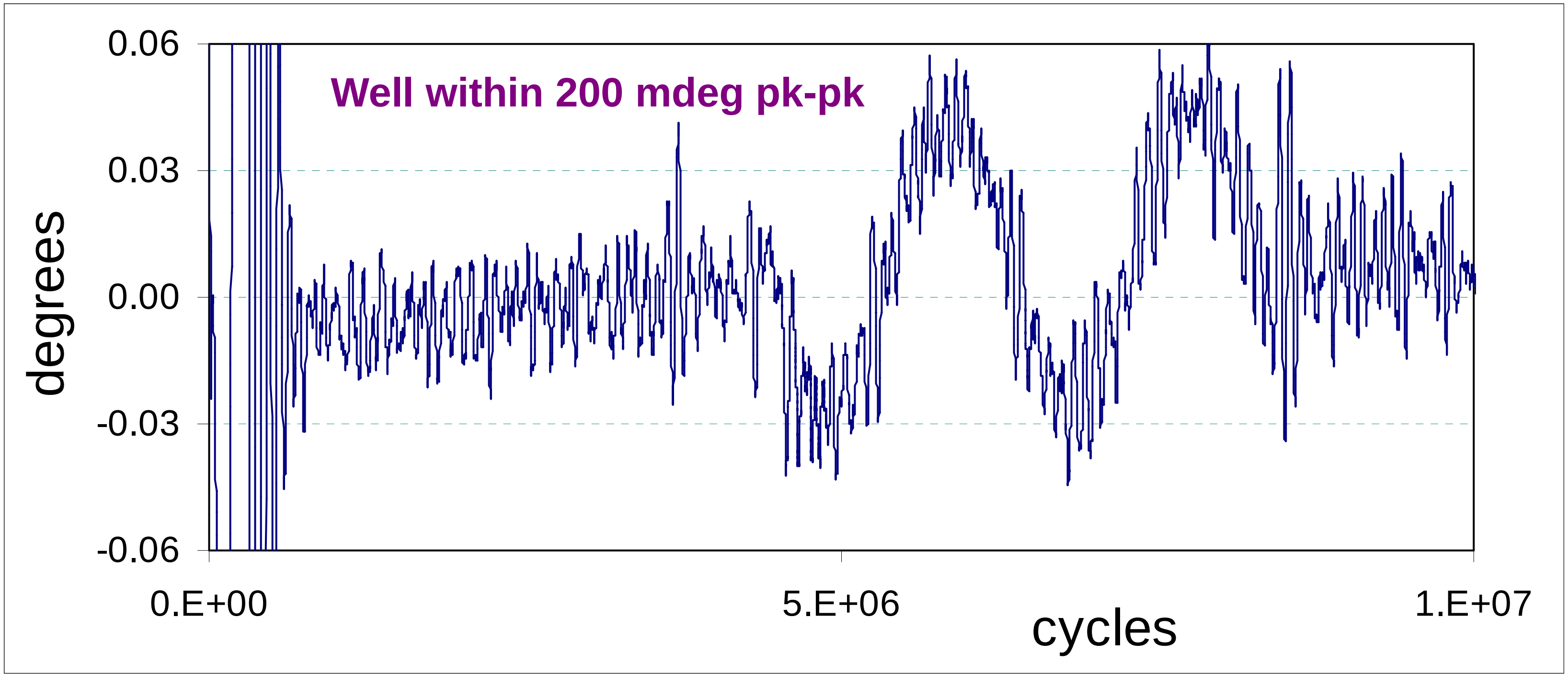
Phase control with measurement error

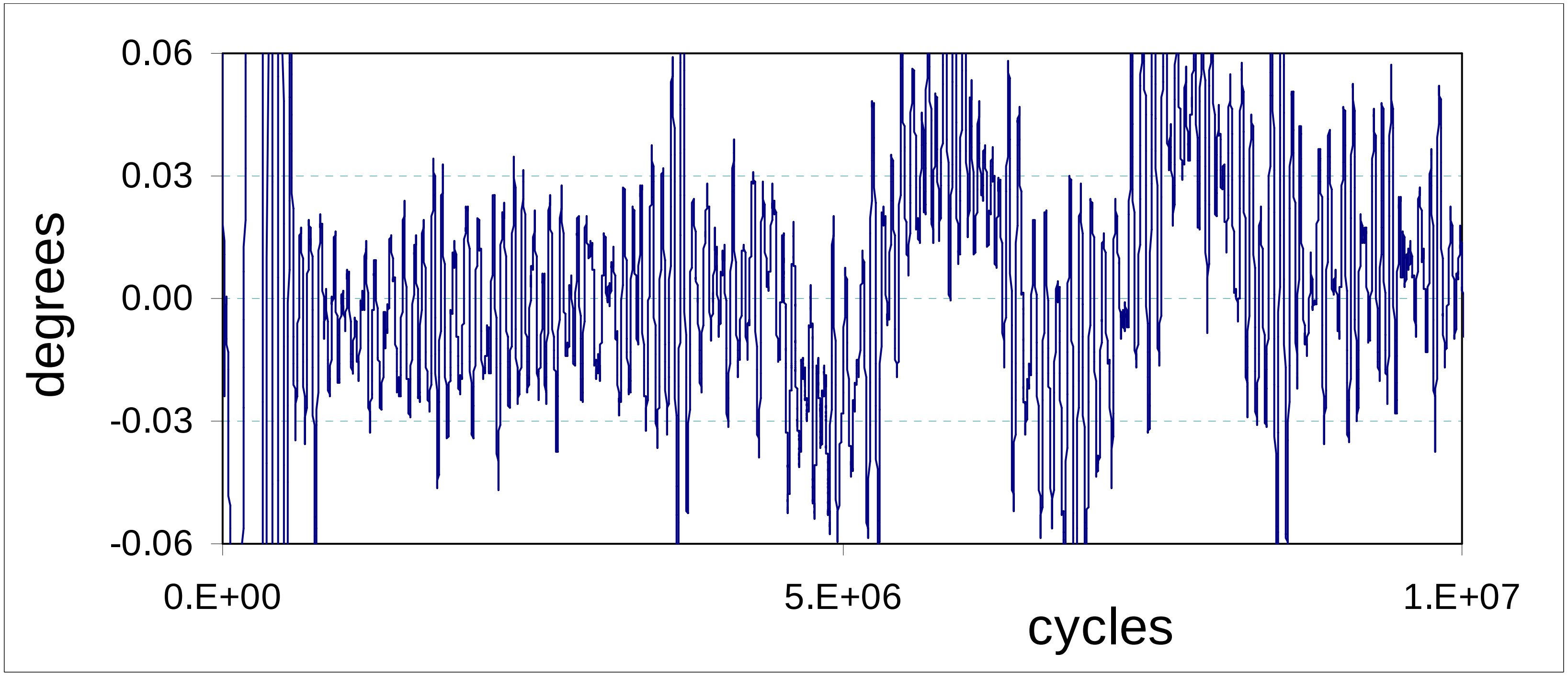
Parameters as before but gain backed off by 20%
with random phase measurement error of +/- 0.020 degrees
and random amplitude measurement error of +/- 0.1 %
measurement signal filter = 500 kHz



Modelling indicates that for a system latency of 1 μs 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 +/- 0.020 degrees
and random amplitude measurement error of +/- 0.3 %
measurement signal filter = 500 kHz



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

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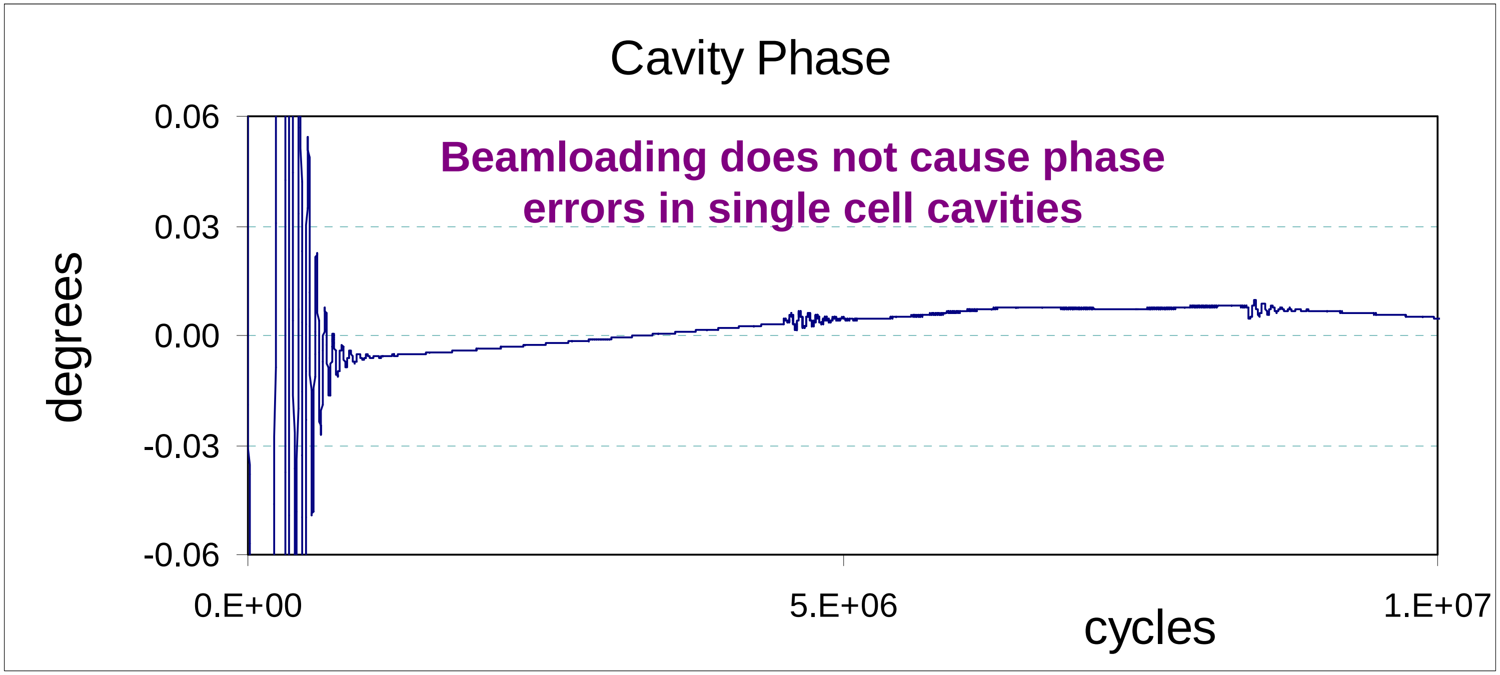
Phase Control for Single Mode Cavity



- No measurement errors included
- Only π mode included
- 0.6 mm oscillating beam offset
- 712 fs random, bunch timing errors
- Control loop latency ~ 1 μs
- Fast oscillation following beamload (0.6 mm oscil.) is removed
- Slow oscillation follows microphonics

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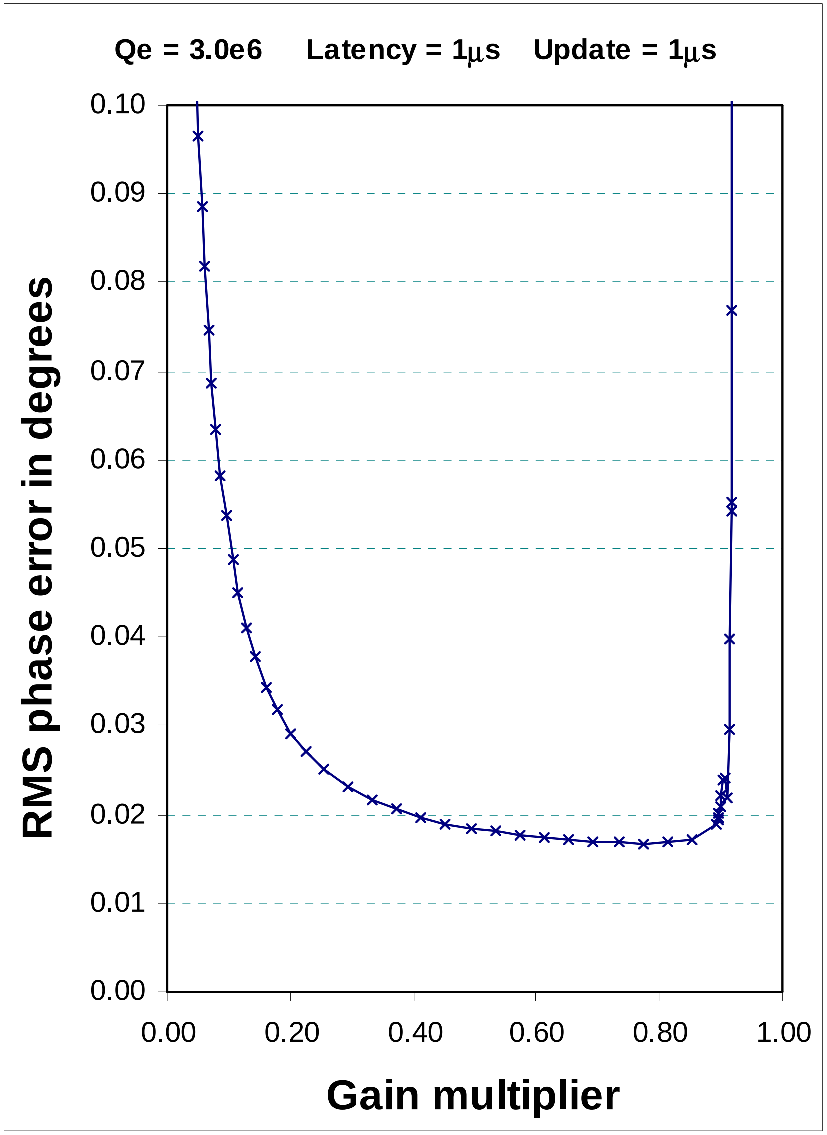
Performance verses gain



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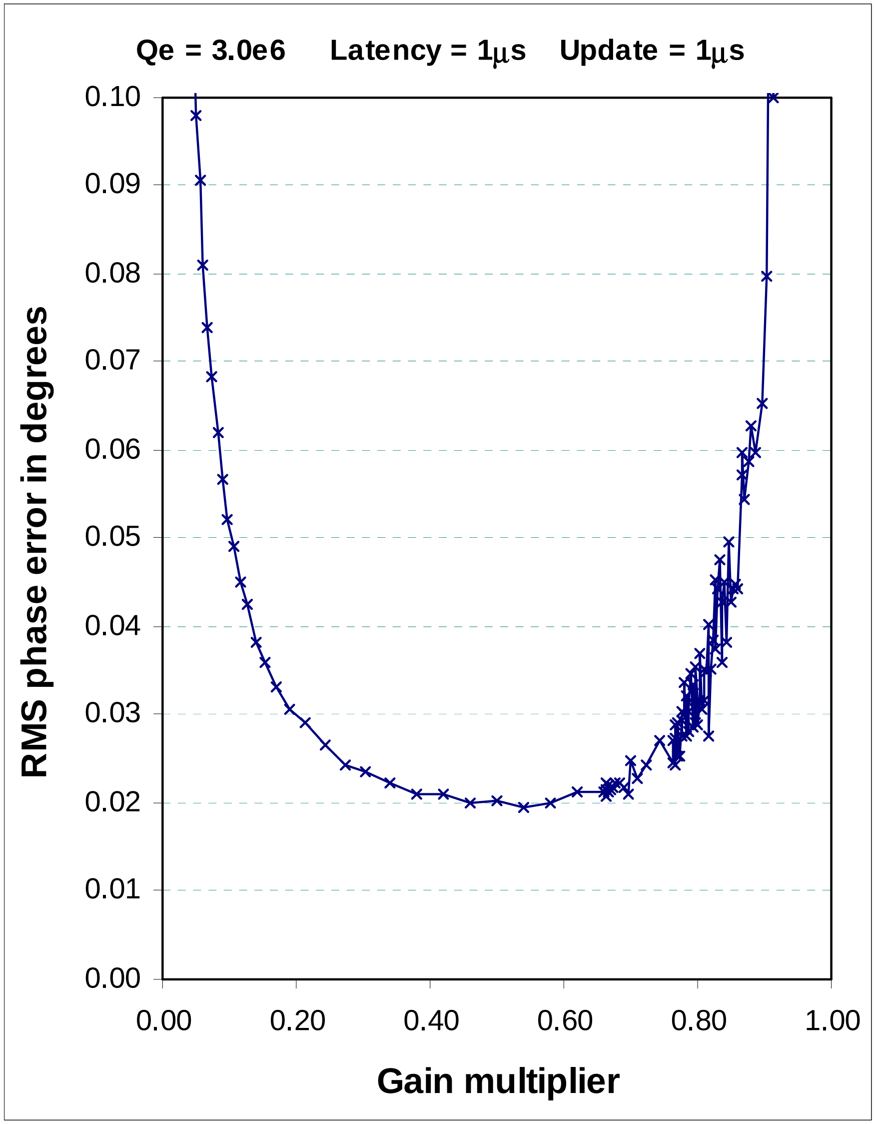
External Q factor	= 3.0E+06
Cavity R over Q (2xFNAL=53 per cell)	= 53.0 ohms
Energy point ILC crab~0.0284J per cell)	= 28.4 mJ
Amplitude set point	= 301.675 kV
Maximum Amplifier Power per cell	= 1200 W
Maximum voltage set point (no beam)	= 1235.476 kV
Maximum beam offset	= 0.6 mm
Maximum bunch phase 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

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)

Cavity Phase Control Conclusion

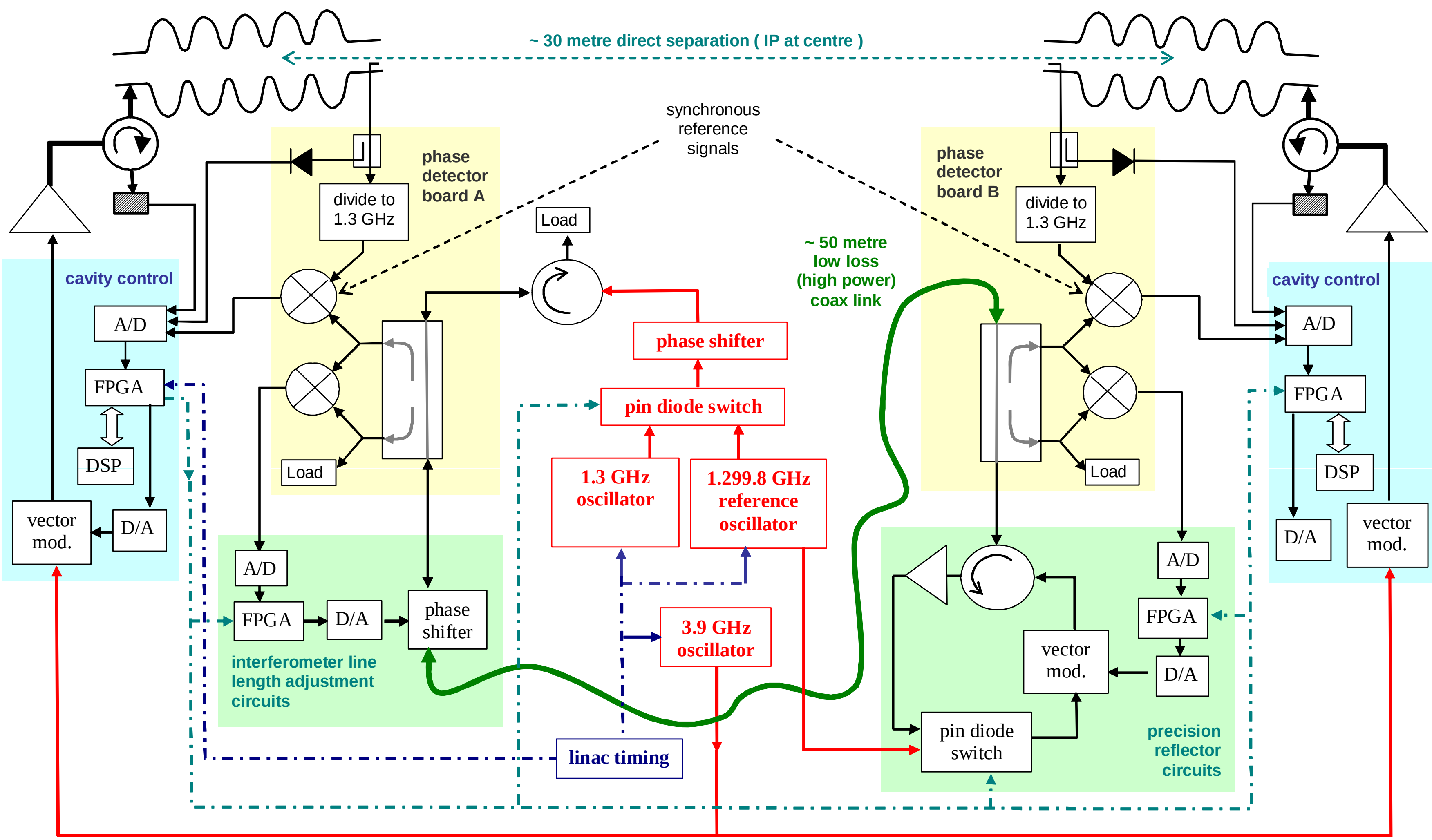
Phase stability performance has been modelled for

- anticipated beam jitter
- levels of microphonics observed in the FNAL CKM cavity
- measurement errors typical for digital phase detectors
- a target latency of 1μs
- Q external optimised for power transfer

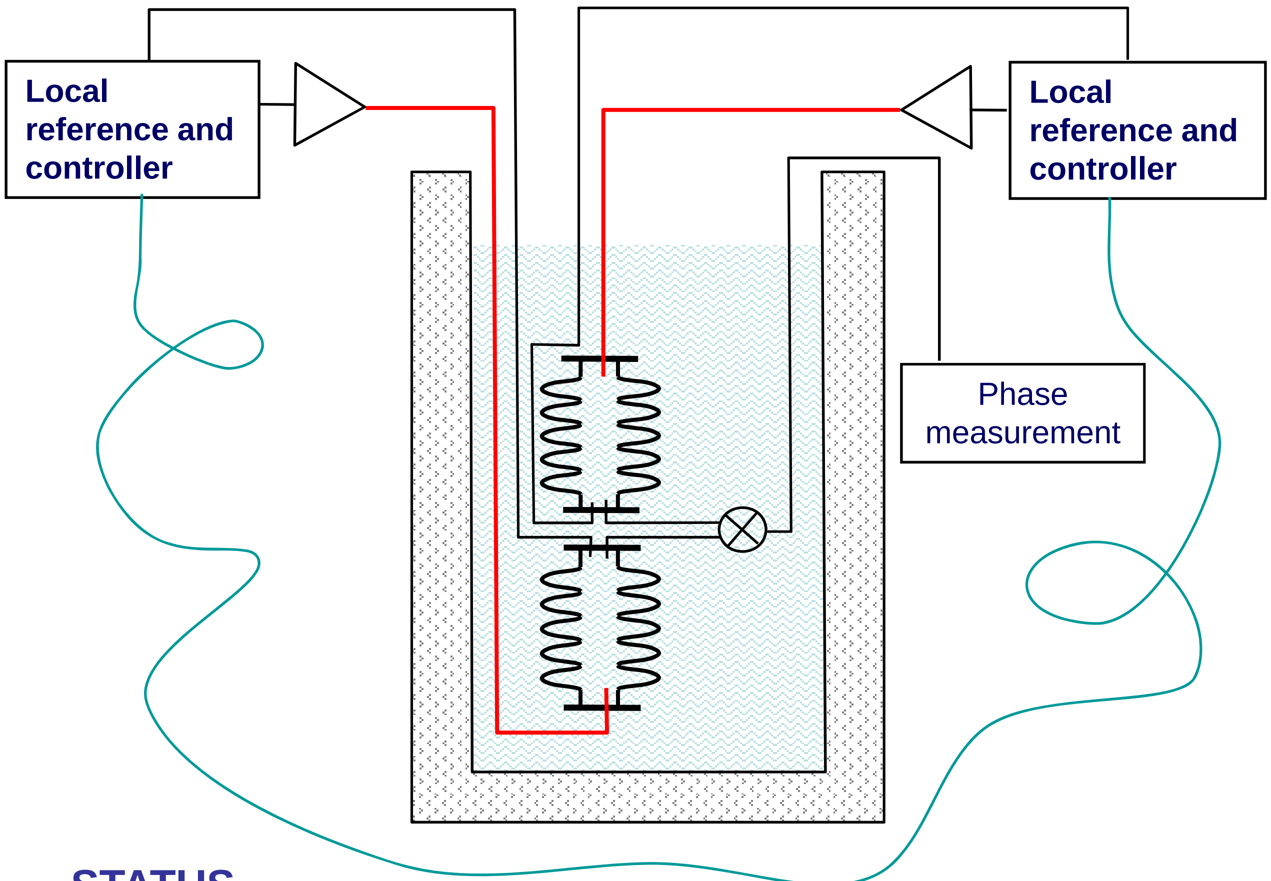
RMS cavity phase jitter at optimum gain was 0.026 degrees

This is within the budget of 0.070 degrees.

Planned Scheme expected ~ 2010



Vertical Cryostat Phase Control Tests

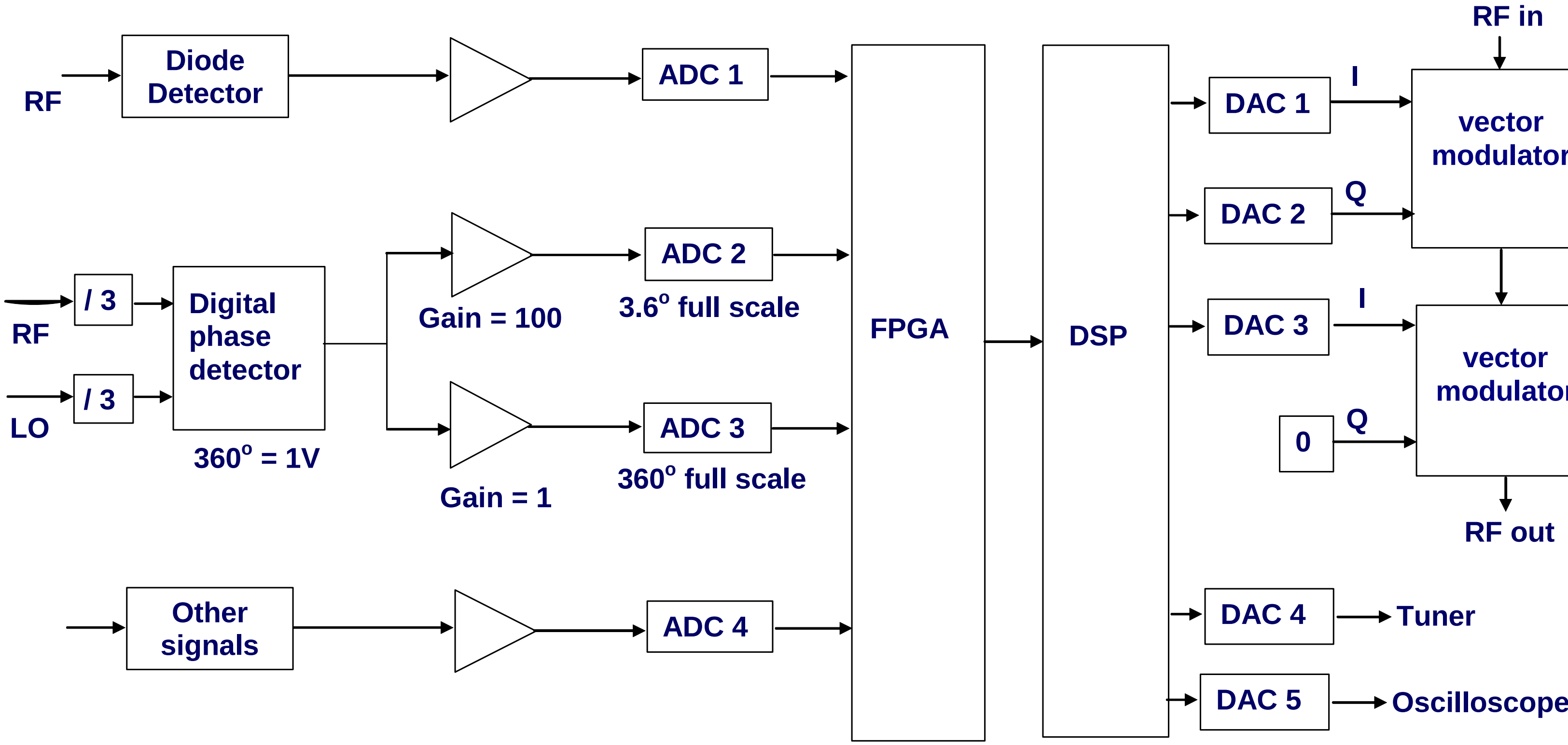


Line to synchronise the local references must have its length continuously measured to with an accuracy of a few microns. On the ILC this line is likely to be between 50m and 80m in length.

STATUS

The cryostat and lid have been manufactured. The superconducting single crab cavities have been manufactured and processed. Installation of the vertical cryostat is in progress. The amplifiers have been delivered. The cavity control boards have been designed and manufactured. The interferometer is under development.

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 the16 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.

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

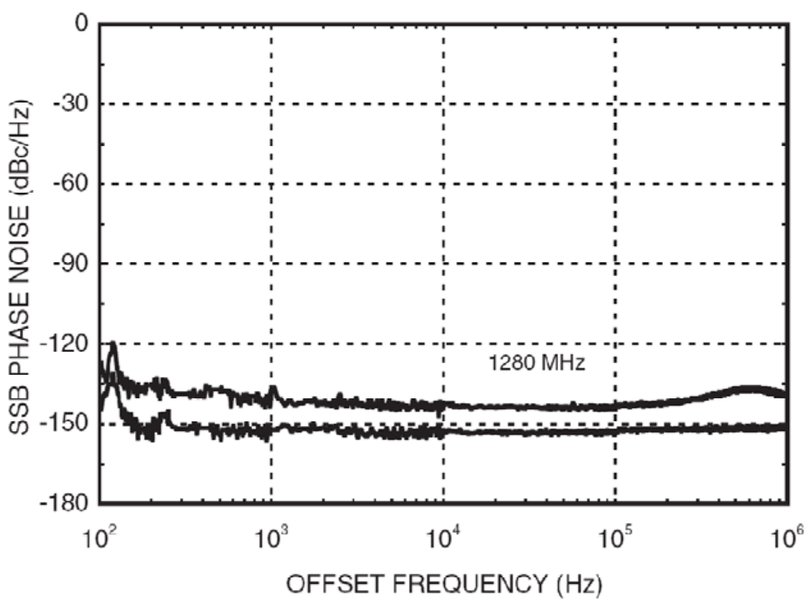
Hittite HMC439QS16G

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

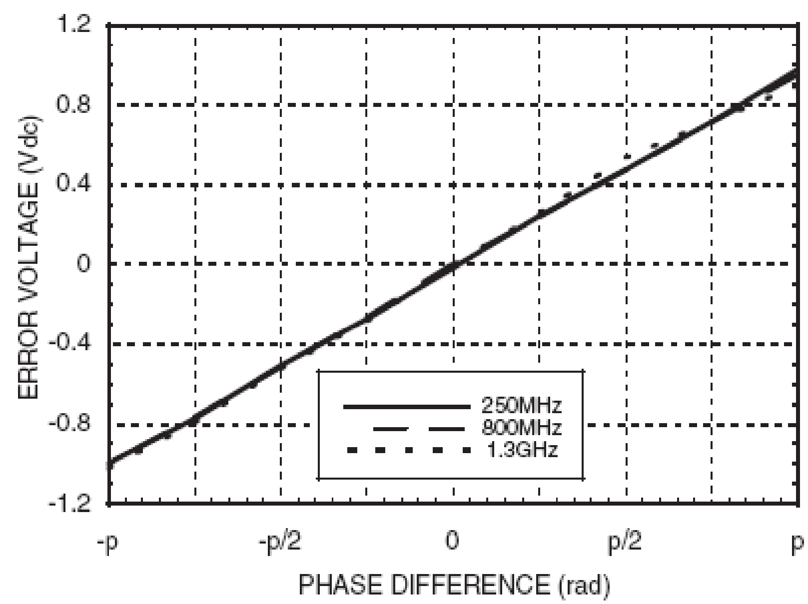
Phase noise (1 MHz bandwidth) ~ -80 dBc

RMS phase jitter = 1.41e-4 radians = 8 milli-degrees = 17 fs

SSB Phase Noise Performance, Pin= 0 dBm, T= 25 °C



Error Voltage vs. Frequency, Pin= 0 dBm*



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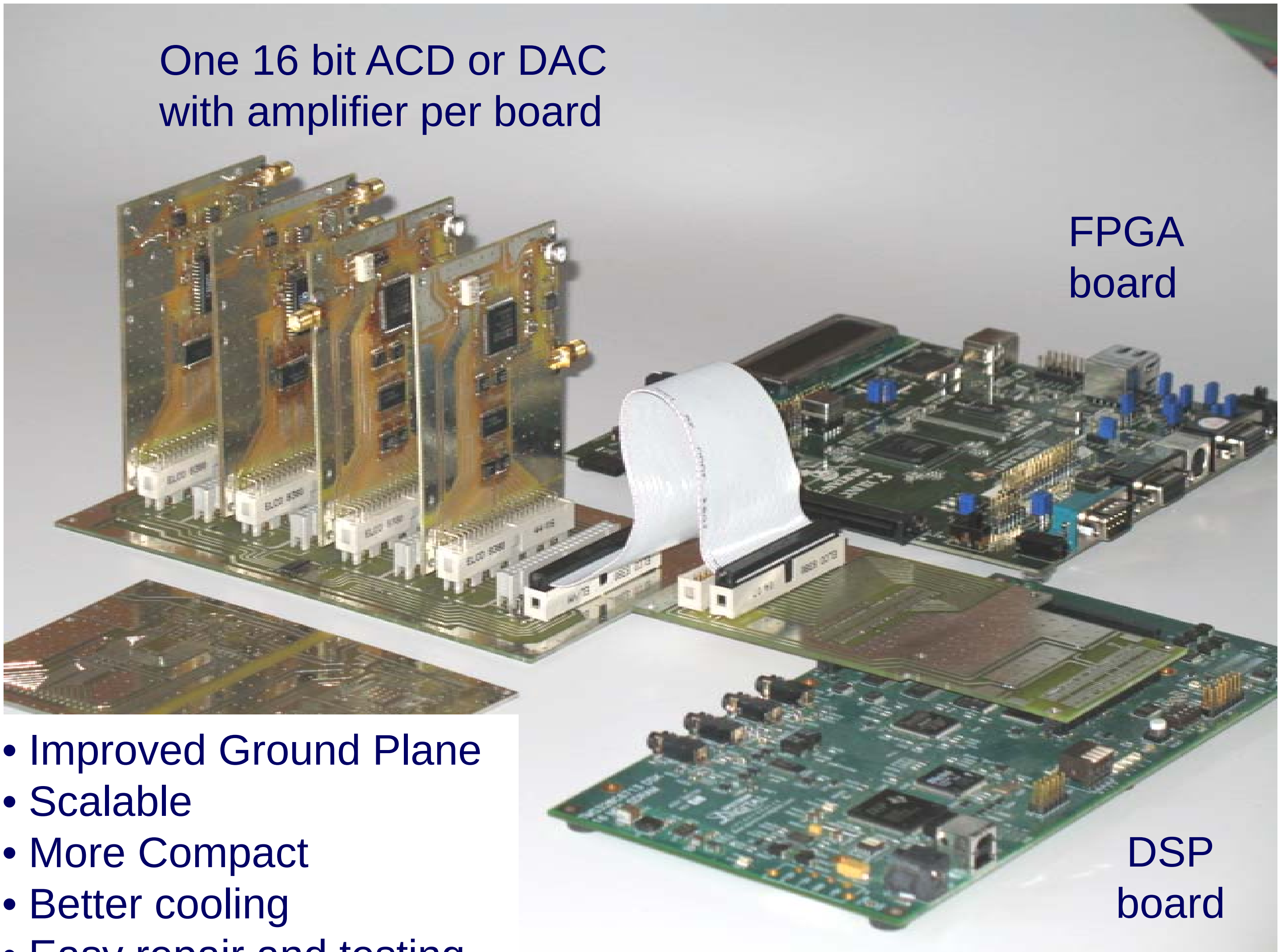
New ADC and DAC Modules



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

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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 ×10 m ~ 66 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^{o}. 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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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.

Absolute Calibration

The phase detector boards are unlikely to offer identical path lengths at the level of 6 μm. 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.

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Planned development tasks

1. Develop monolithic phase detector board. (currently we use discrete components).
2. Interface FPGA to DSP on cavity control board.
3. Replace analog. loop filter on interferometer with FPGA controllers.
4. Complete interferometer simulations.
5. Link interferometer model to cavity control model and check stability.
6. Develop automatic calibration of interferometer.
7. Develop interface with cavity tuners.
8. Performance test on pairs of superconducting cavities at 1.3 GHz and 3.9 GHz.
9. Investigate the applicability of advanced control algorithms beyond PI.
10. Develop RF controller for active damping of the SOM.