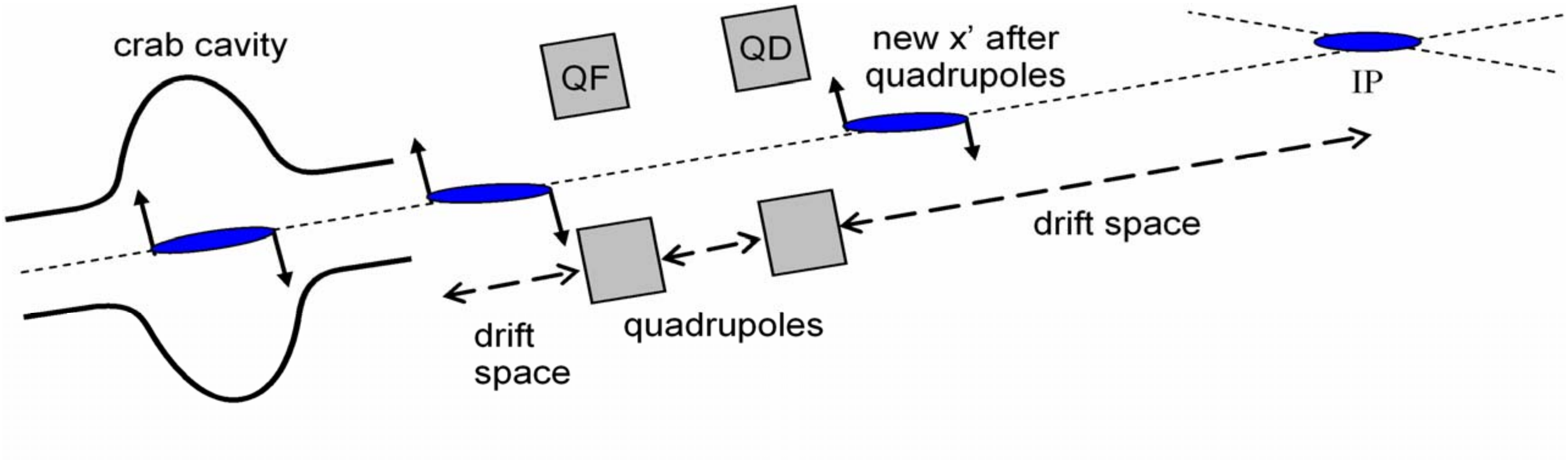
ILC Crab Cavity Collaboration

- **Cockcroft Institute :**
  - Graeme Burt (Lancaster University)
  - Richard Carter (Lancaster University)
  - Amos Dexter (Lancaster University)
  - Philippe Goudket (ASTeC)
  - Roger Jones (Manchester University)
  - Alex Kalinin (ASTeC)
  - Lili Ma (ASTeC)
  - Peter McIntosh (ASTeC)
  - Imran Tahir (Lancaster University)

- **FNAL**
  - Leo Bellantoni
  - Mike Church
  - Tim Koeth
  - Timergali Khabiboulline
  - Nikolay Solyak

- **SLAC**
  - Chris Adolphson
  - Kwok Ko
  - Zenghai Li
  - Cho Ng

Crab Cavity Function



The crab cavity is a deflection cavity operated with a 90^o phase shift.

A particle at the centre of the bunch gets no transverse momentum kick and hence no deflection at the IP.

A particle at the front gets a transverse momentum that is equal and opposite to a particle at the back.

The quadrupoles change the rate of rotation of the bunch.

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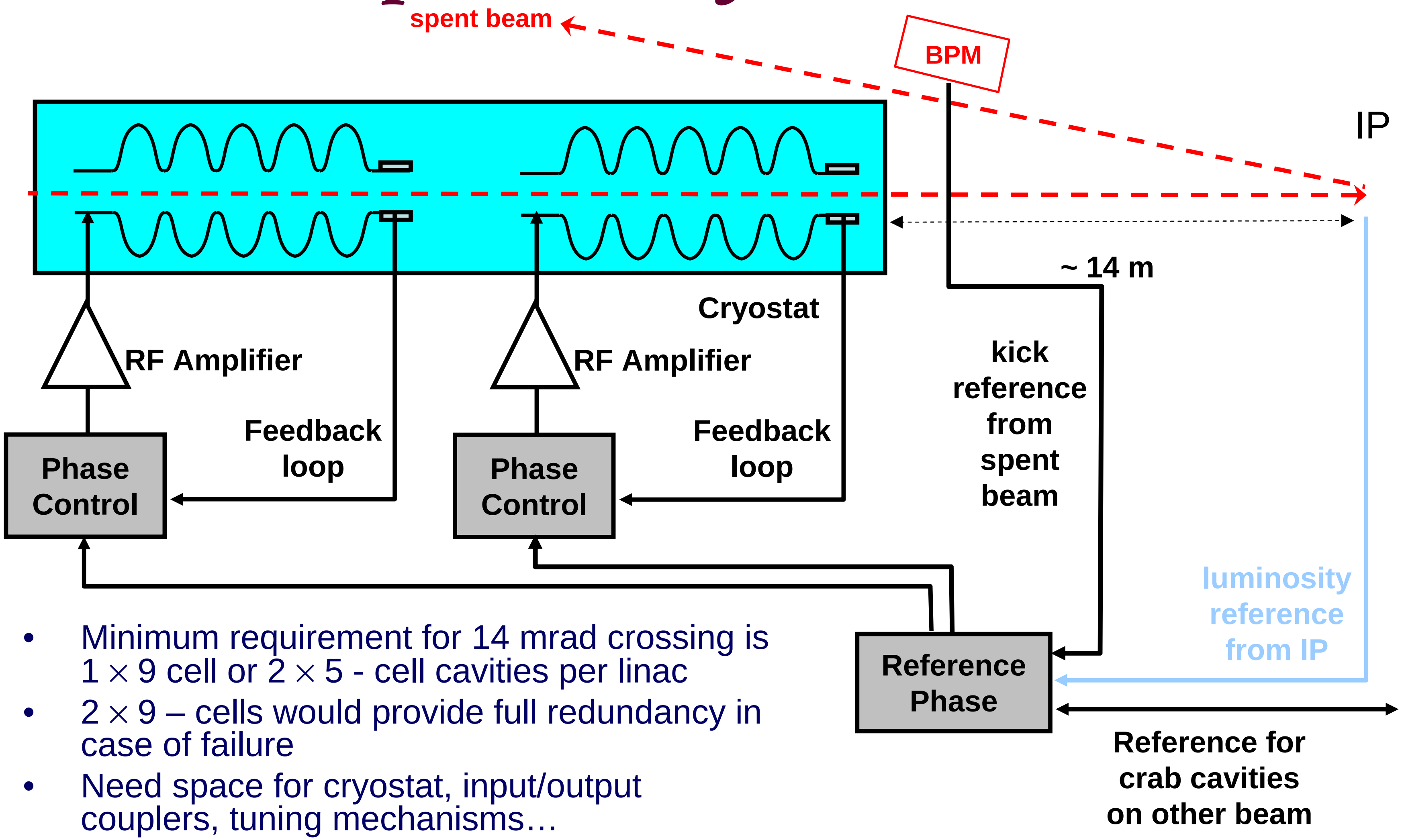
RDR Crab Cavity Parameters

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	0.1°
RMS amplitude stability for 2% rms Luminosity drop	1.2%
Potential X beam jitter at crab cavity, μm	500 μm
Potential Y beam jitter at crab cavity, μm	35 μm

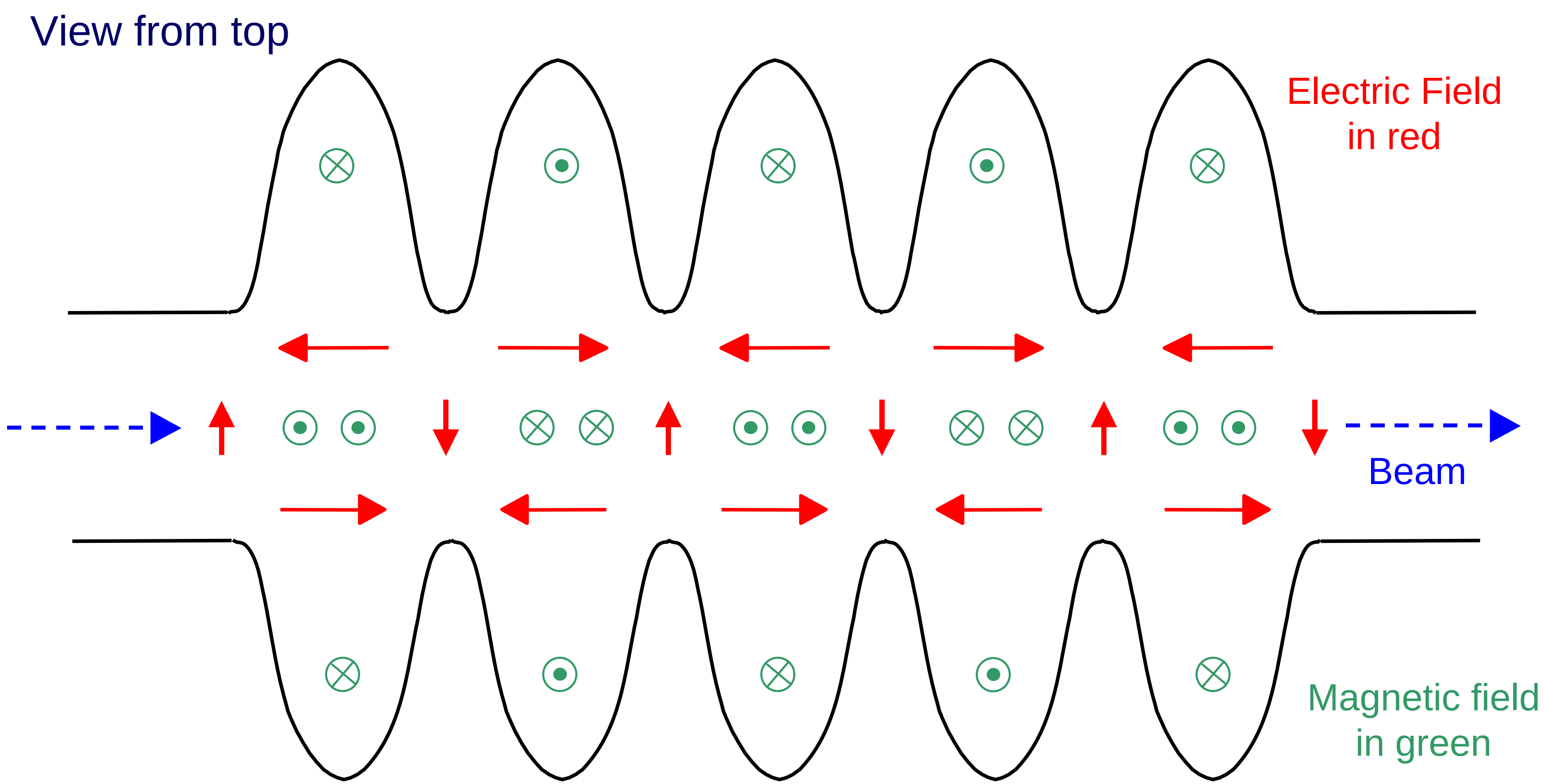
For 500 GeV CM we might use 1 nine cell cavity or two 5 cell cavities

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…

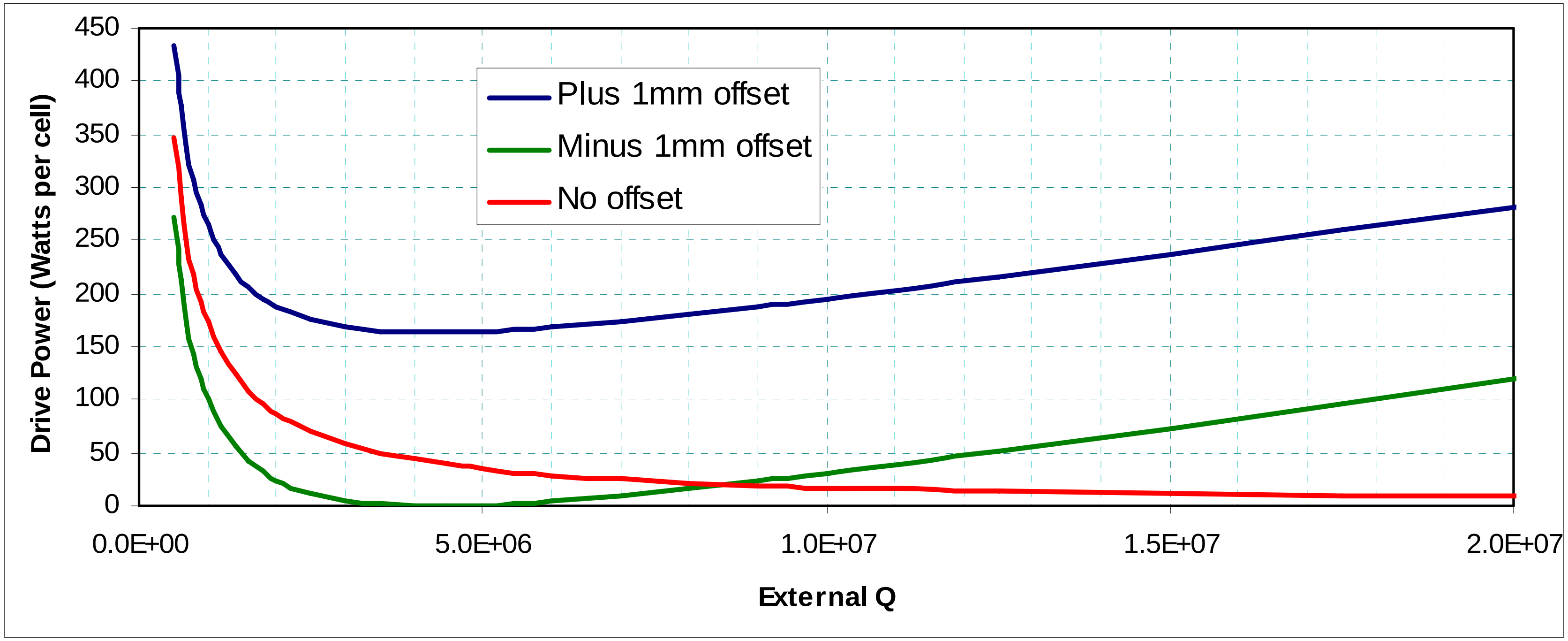
TM110 Dipole mode cavity



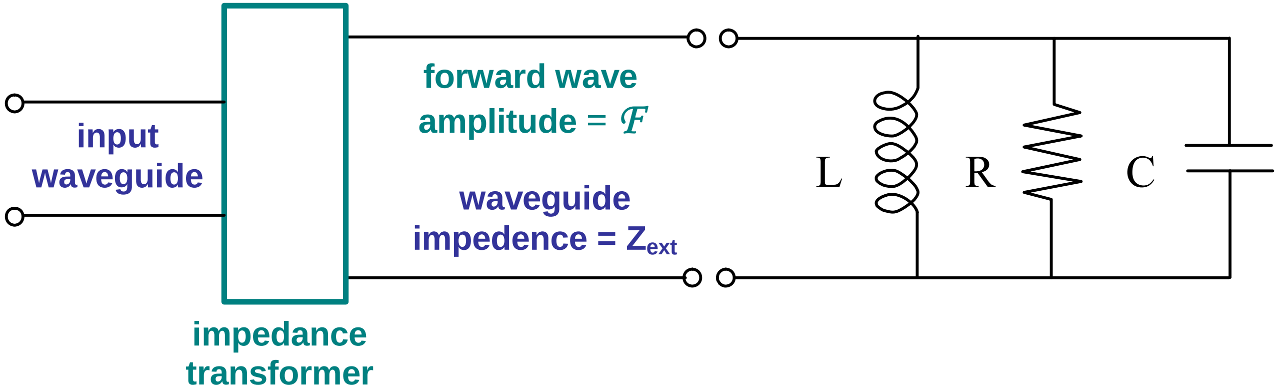
For a crab cavity the bunch centre is at the cell centre when E is maximum and B is zero

Beamloading

- Longitudinal electric field on axis is zero for dipole mode
- Beamloading loading is zero for on axis bunches
- Bunches pass cavity centre when B transverse = 0 hence of 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



Phase Control Model



equivalent electrical circuit for excitation of a single cavity mode

$$\frac{d^2V}{dt^2} + \left(\frac{1}{Q_o}+\frac{1}{Q_e}\right)\omega_o \frac{dV}{dt} + \omega_o^2 V = \frac{2\omega_o}{Q_e}\frac{d}{dt}\left\{\mathcal{F}\exp(-j\omega t)\right\}$$

resulting differential equation

$$Q_o = \omega_o R C \qquad \omega_o = \frac{1}{\sqrt{LC}} \qquad \frac{Q_e}{Q_o} = \frac{Z_{wg}}{R}$$

conversion from circuit parameters to cavity parameters

- Microphonics cause ω_o 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

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 Watt 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

Hence solve envelope equations defined by

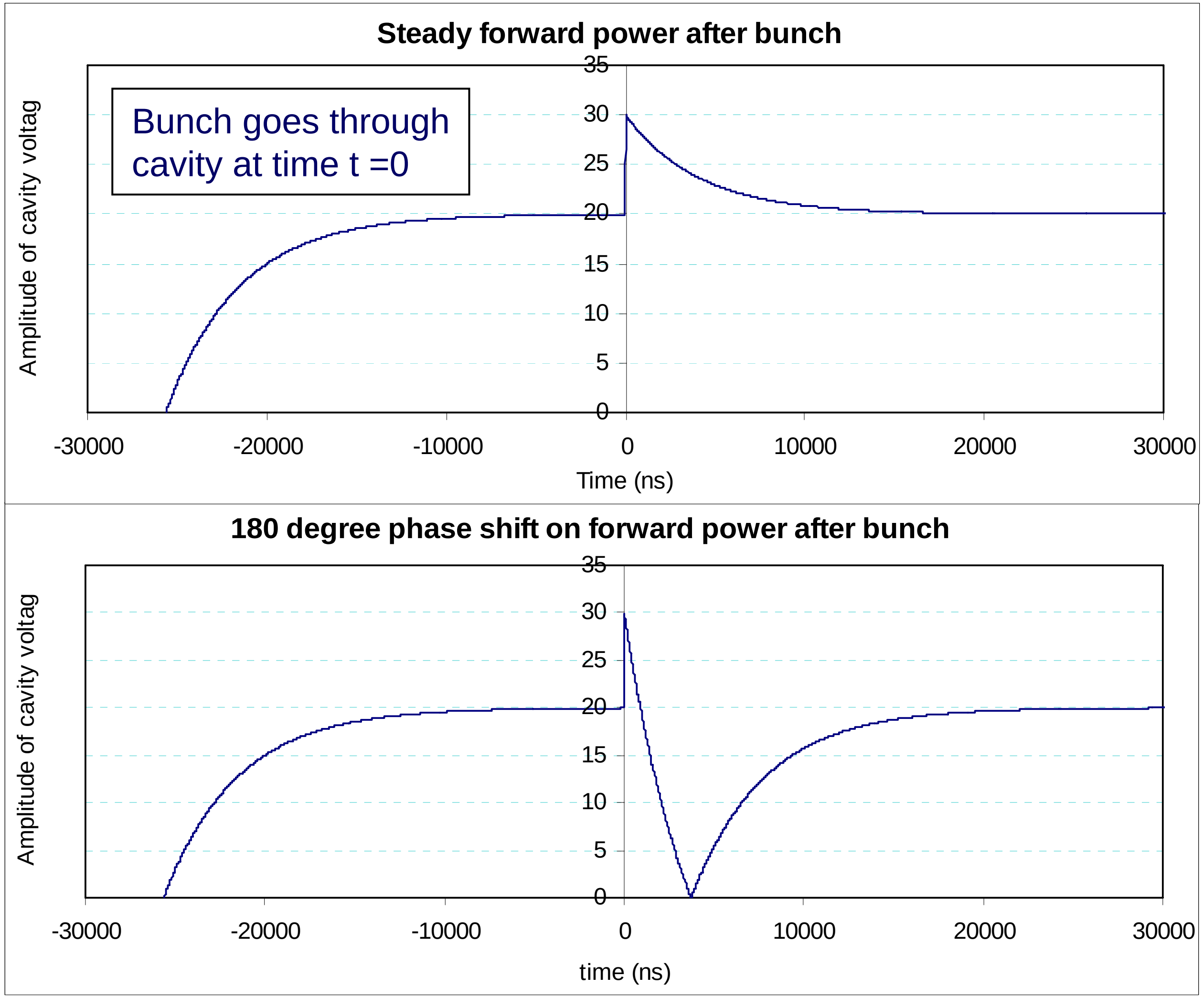
$$V(t) = \left\{ A_r(t) + jA_i(t) \right\} \exp\left\{ -j\omega t \right\}$$

$$\frac{1}{\omega_o}\dot{A}_r + \frac{1}{4}\left(1+\frac{\omega_o^2}{\omega^2}\right)\frac{1}{Q_L}A_r - \frac{1}{2}\left(\frac{\omega_o}{\omega}-\frac{\omega}{\omega_o}\right)A_i = -\frac{1}{Q_e}\frac{\omega_o}{\omega}\left(\frac{1}{\omega_o}\dot{\mathcal{F}}_i - \frac{\omega}{\omega_o}\mathcal{F}_r\right)$$

$$\frac{1}{\omega_o}\dot{A}_i + \frac{1}{4}\left(1+\frac{\omega_o^2}{\omega^2}\right)\frac{1}{Q_L}A_i + \frac{1}{2}\left(\frac{\omega_o}{\omega}-\frac{\omega}{\omega_o}\right)A_r = \frac{1}{Q_e}\frac{\omega_o}{\omega}\left(\frac{1}{\omega_o}\dot{\mathcal{F}}_r + \frac{\omega}{\omega_o}\mathcal{F}_i\right)$$

This form assumes $Q_o >> Q_e$ note that $Q_L = Q_o + Q_e$

Using amplifier to extract cavity energy



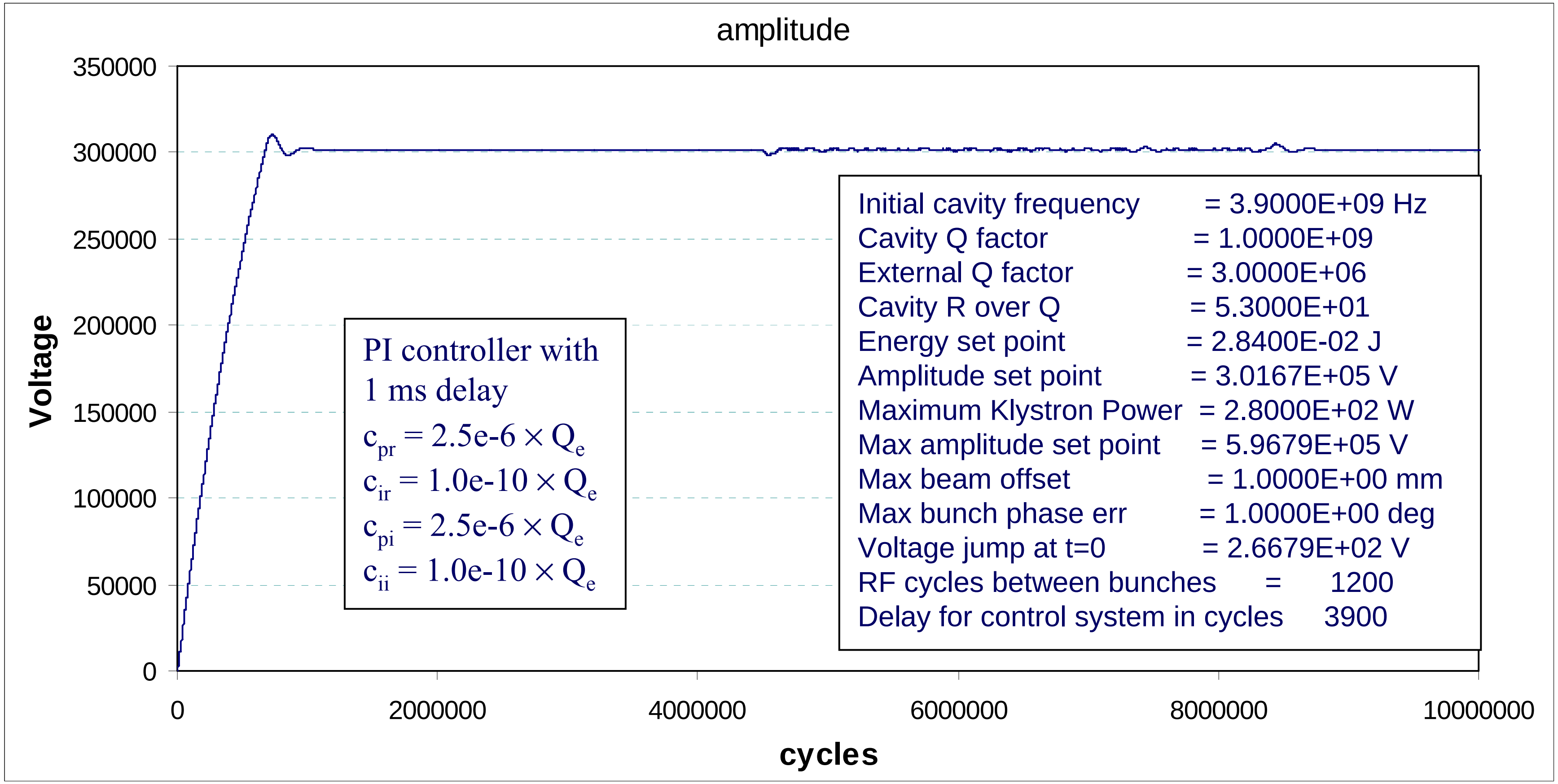
For the crab cavity the bunches can supply or remove energy.

Whilst in principle the amplifier can be used to reduce cavity energy after shifting its phase by 180º this is undesirable when one is trying to control cavity phase.

It is desirable to chose a low external Q so this never needs to happen.

Modelling of cavity amplitude (no microphonics)

Random bunch to bunch offset of 1 mm and arrival phase of 1 degree



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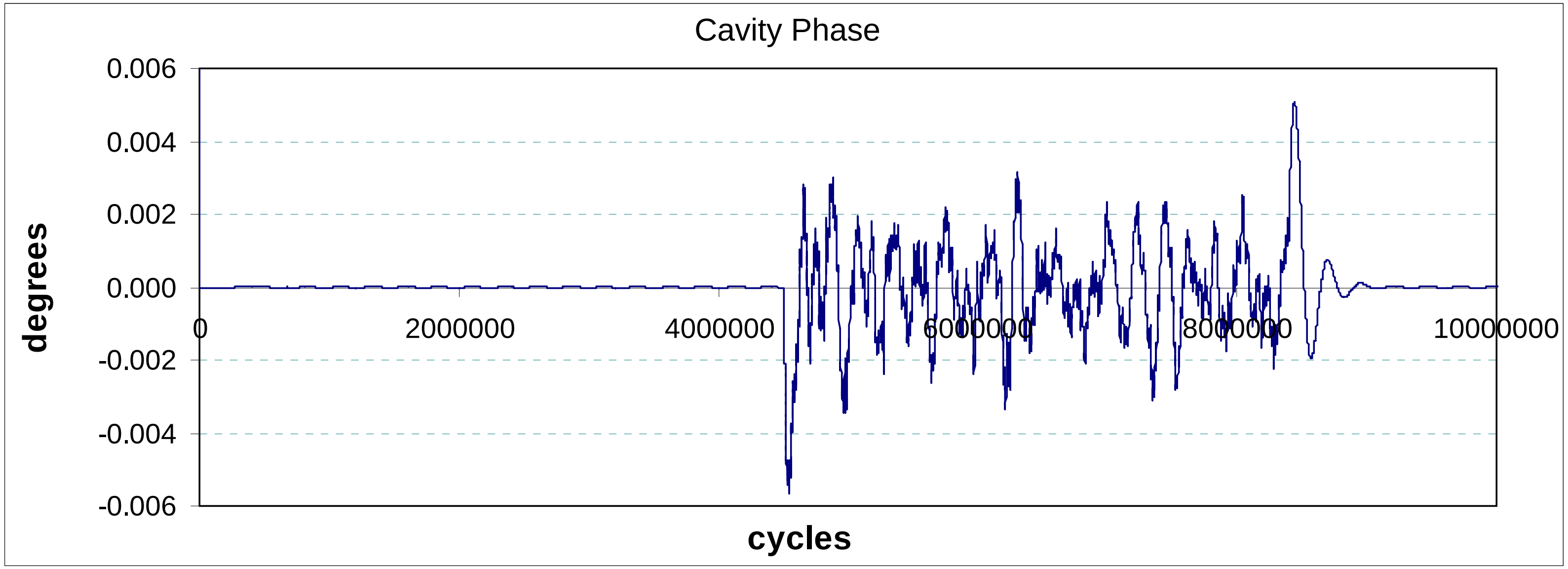
Modelling of cavity phase (no microphonics)

Random bunch to bunch offset of 1 mm and arrival phase of 1 degree

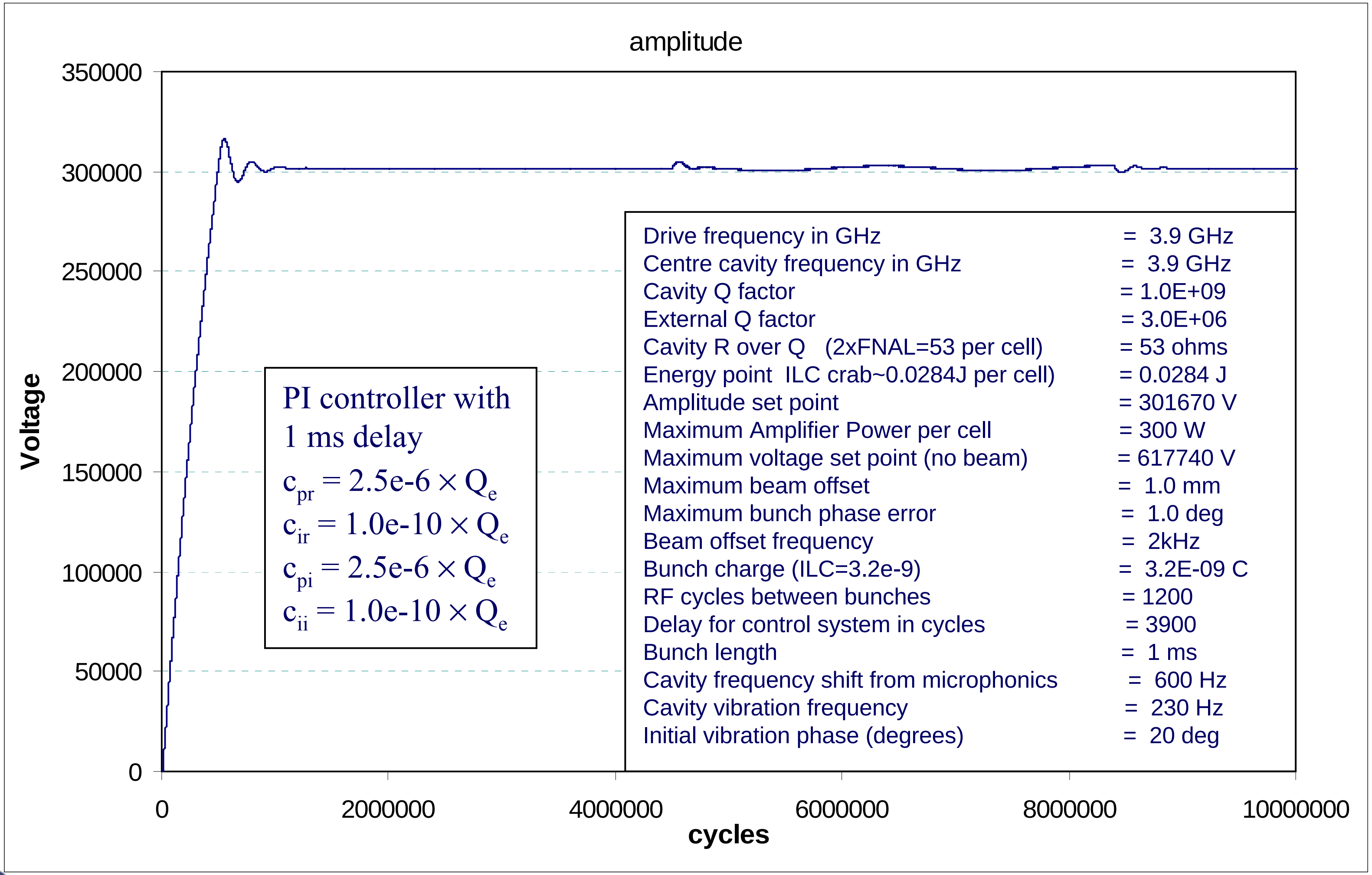


Beam loading does not give an special problems in stabilizing the phase

ilc international linear collider

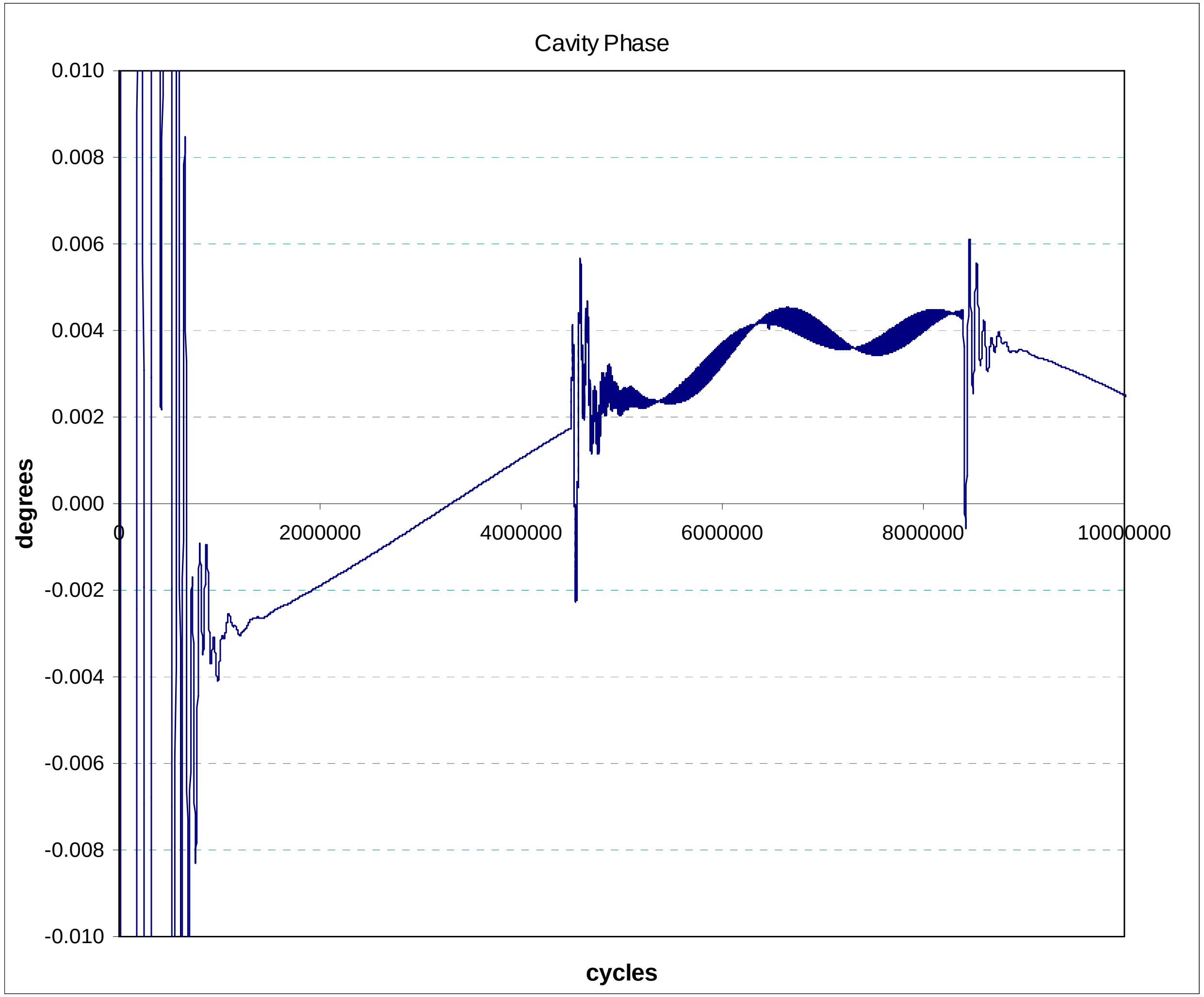
Modelling of cavity amplitude with microphonics

Oscillatory bunch offset of 1 mm and random arrival phase of 1 degree

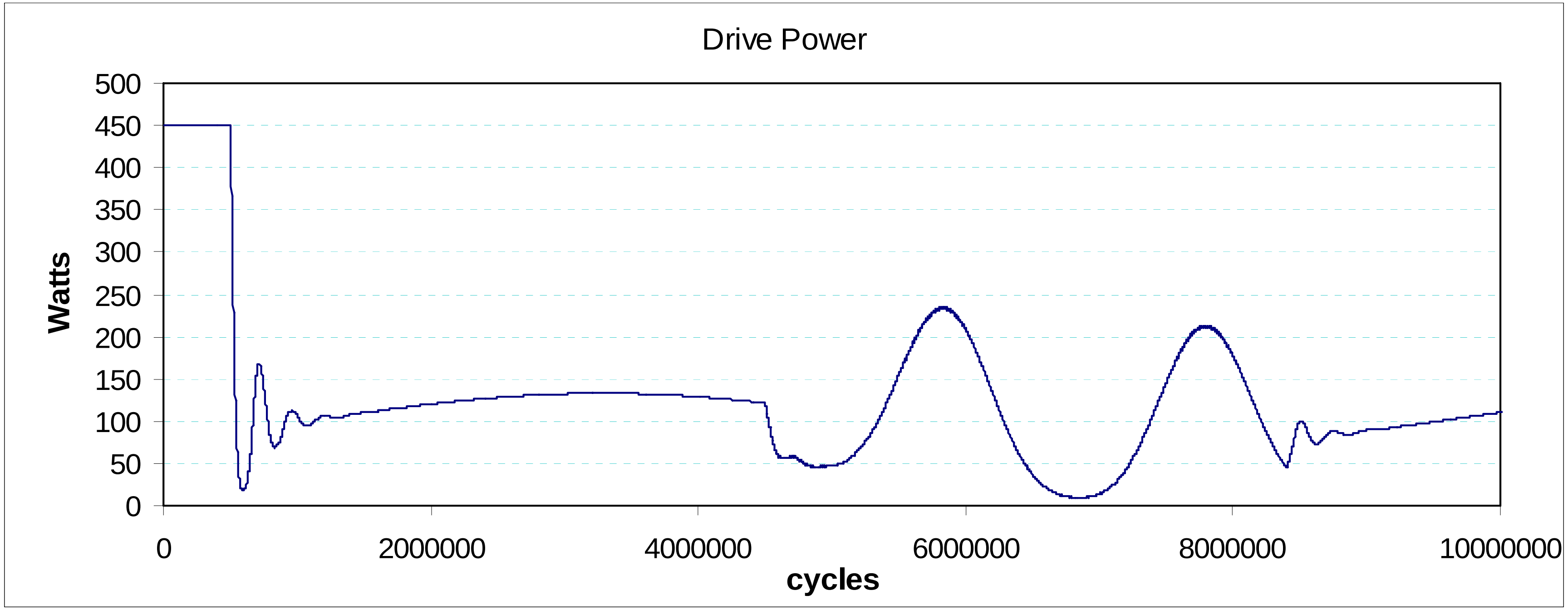


Modelling of cavity phase with microphonics

Oscillatory bunch offset of 1 mm and random arrival phase of 1 degree

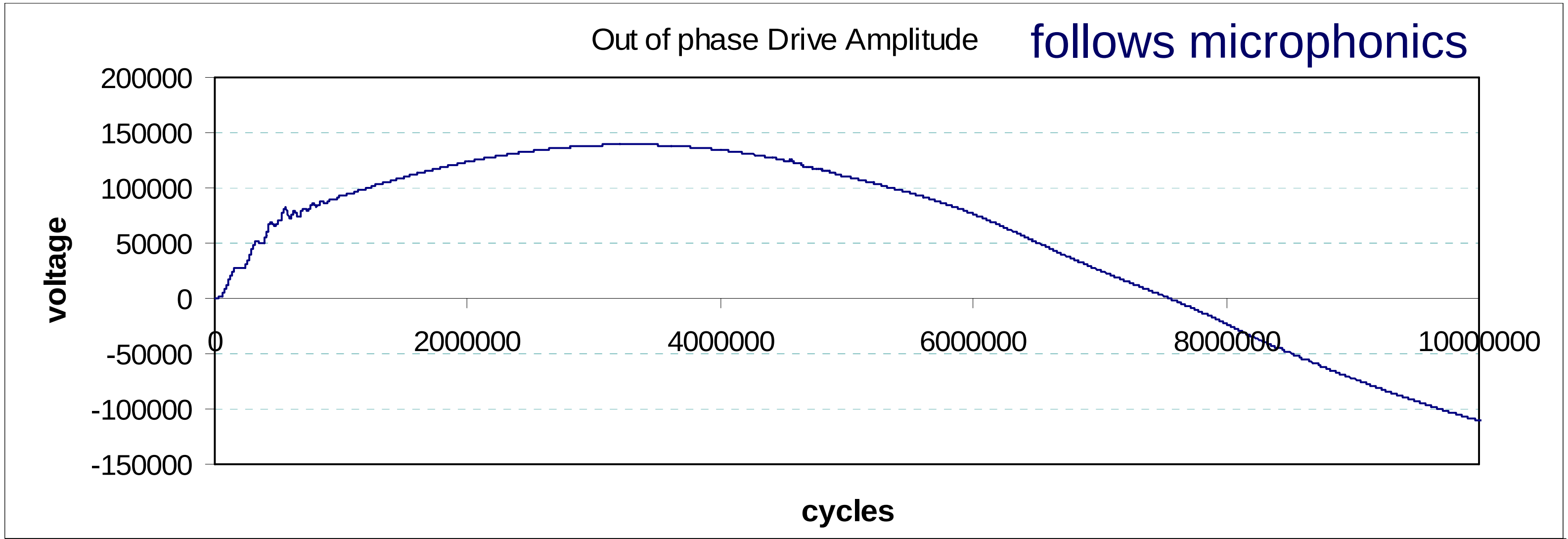


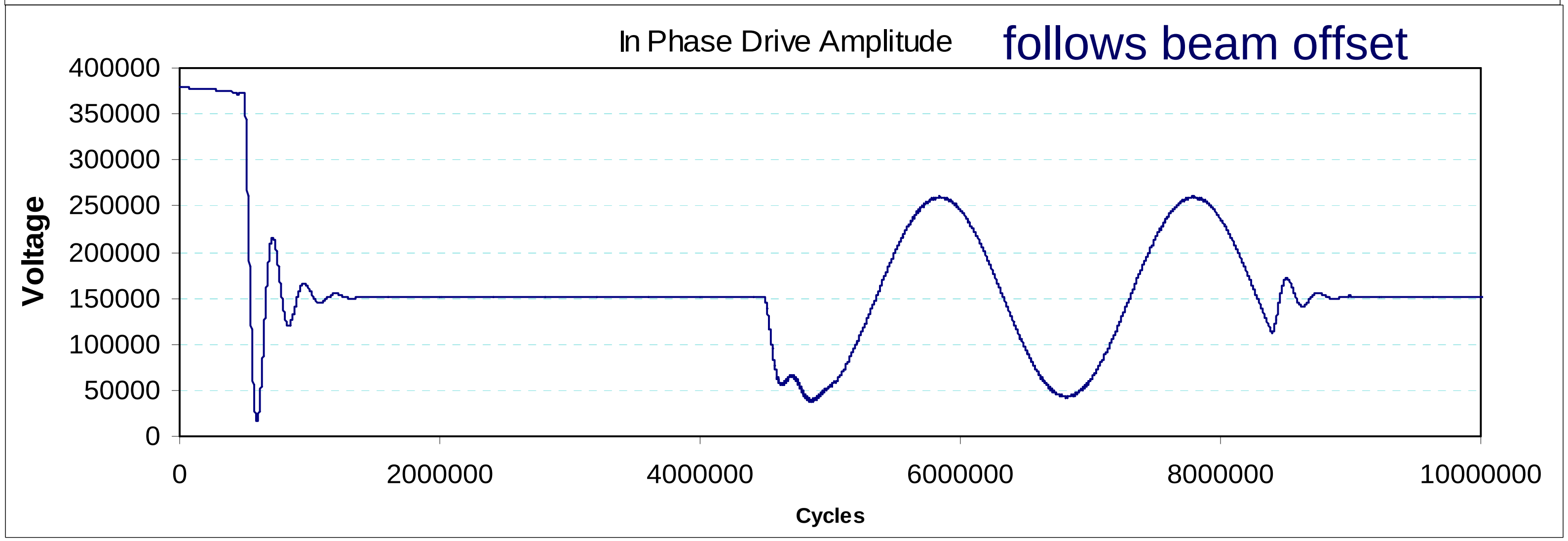
Modelling of cavity drive power with microphonics



- A single klystron can't easily do this but solid state amplifiers can.
- To work with a Klystron we must lower the external Q

Modelling of cavity drive with microphonics





Model refinement

- Still need to add detailed amplifier models
- A measurement model
- Alternative controllers

Phase Control Development

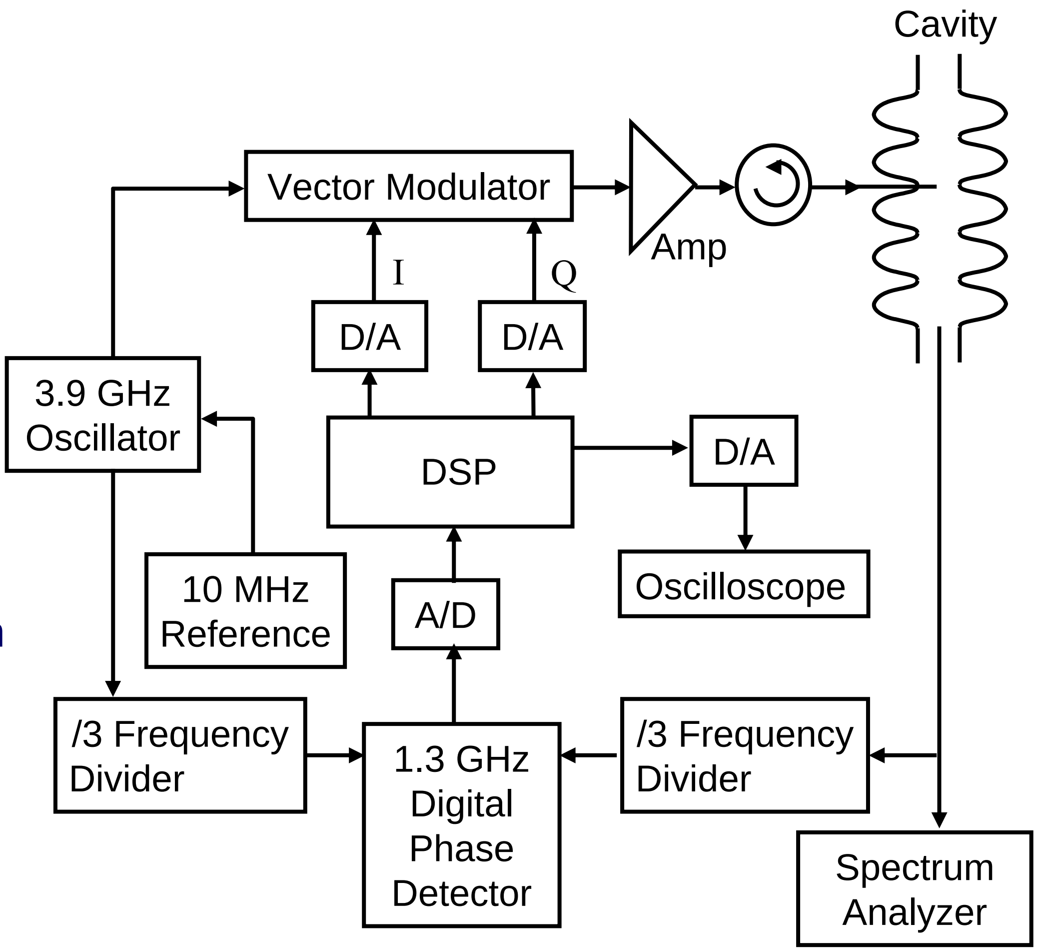
Vector modulation available to 4 GHz

Digital phase detection currently under investigation will eventually be used alongside a mixer and digital IQ detection at an intermediate frequency as used on flash.

Have improved precision of measurement since August by upgrading ADC and DAC from 12bit to fast 16bit.

Programmed basic control software in DSP and have demonstrated phase locking of warm cavity to 0.02 degrees rms so far.

Need to upgrade connectors, cabling and low noise amplifiers



Issues in developing 16 bit ADC and DAC boards

- The phase control work at Lancaster is focusing on the use of a digital phase detector with 16 bit ADC and DAC conversion.
- One of the remaining problems is getting the d.c. voltage output from the phase detector into the ADC without picking up noise.
- DESY abandoned this approach as they could not get the same performance as can be achieved by transferring phase information into the DSP on an intermediate carrier frequency from a double balanced mixer.
- The digital phase detector offers an absolute measurement without calibration and can be used alongside phase quadrature measurements at an intermediate frequency which are necessary to give amplitude.

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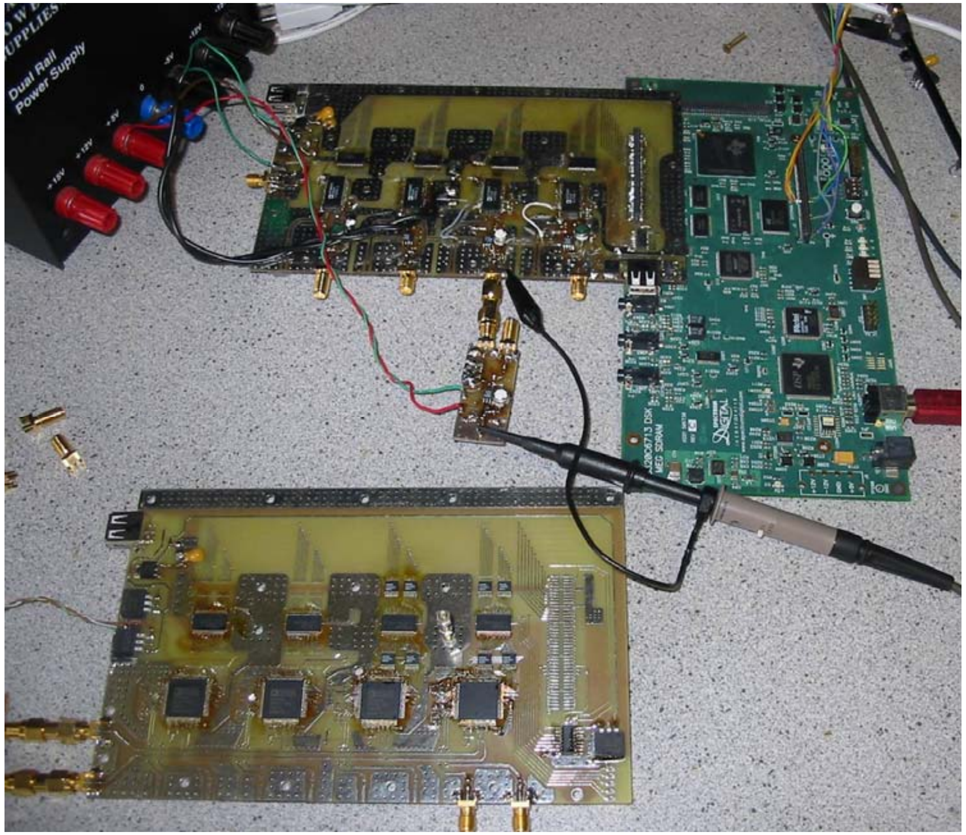
Development of 16 bit DAC & ADC



ADC

16 bit gives resolution of 5.6 mdeg in 360 degrees

latency = 130 ns

sample rate = 100 Mbits/s

rms noise ~ ± 2.4 bits
so need to average 8 or more bits
which takes ~ 100 ns

Digital Phase Detector resolution
~ 5 mdeg

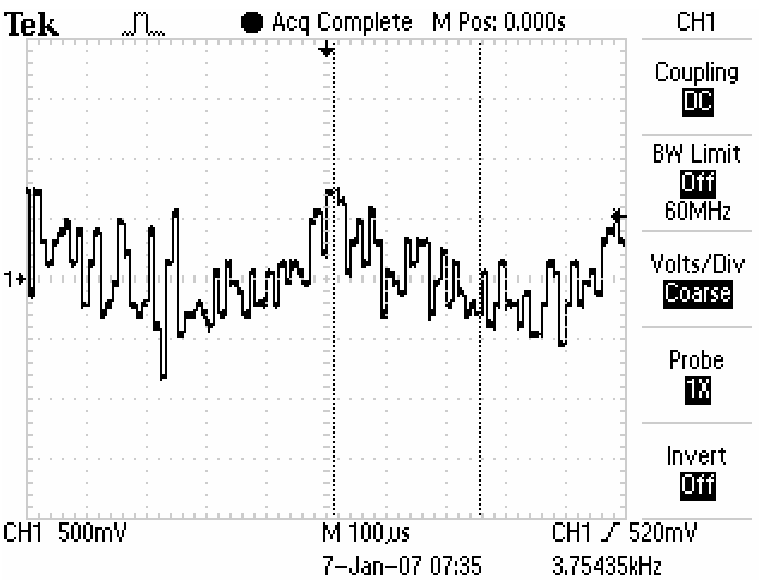
DAC
settling time ~ 10 ns

DSP
Have yet to implement FPGAs hence slow read & write
read time to DSP ~300 ns write time to DAC ~200 ns.
still using in built functions to get Sine and Cosine for
vector modulator hence processing is a little slow.

Have potential to react to a phase error of 5 mdeg in 2-3 μs.

Status of measurement precision

Precision of the measurement is determined by looking at the jitter on the DAC input to the vector modulator when a controller in the DSP is used to phase lock a low Q cavity.

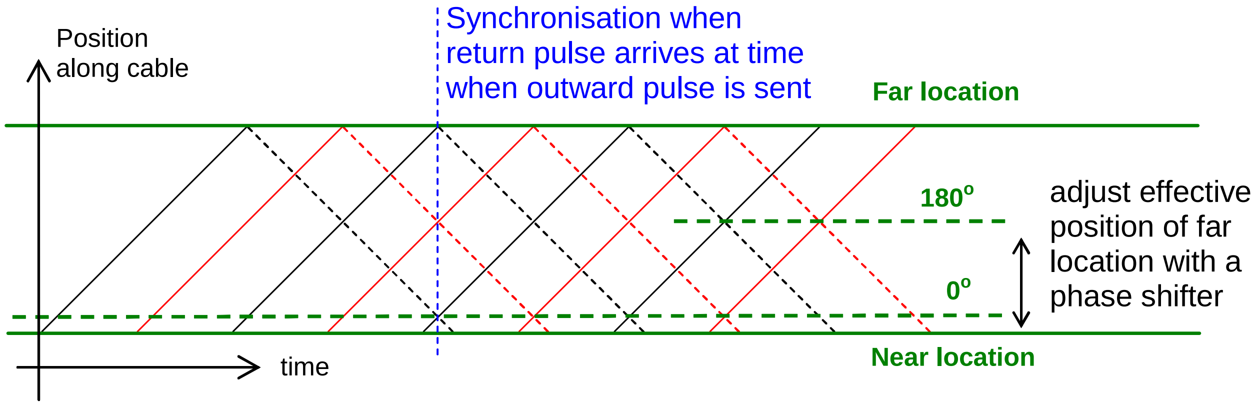


We now controlling close to the noise level on the ADC (3 bits)

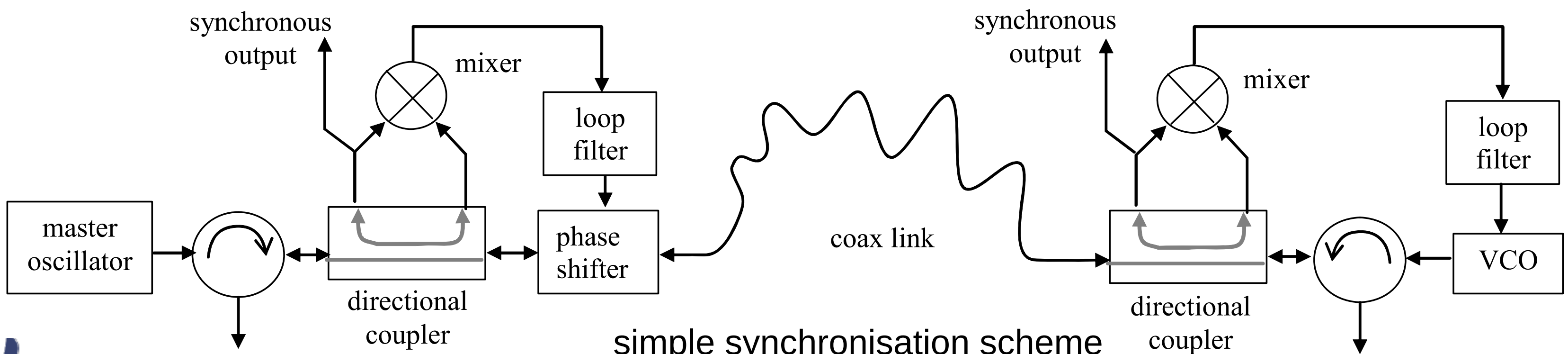
We still have ripple from a miss match on the ADC input which is d.c. coupled.

Next we need to re-instate an independent measurement of jitter using a double balance mixer.

Phase synchronisation

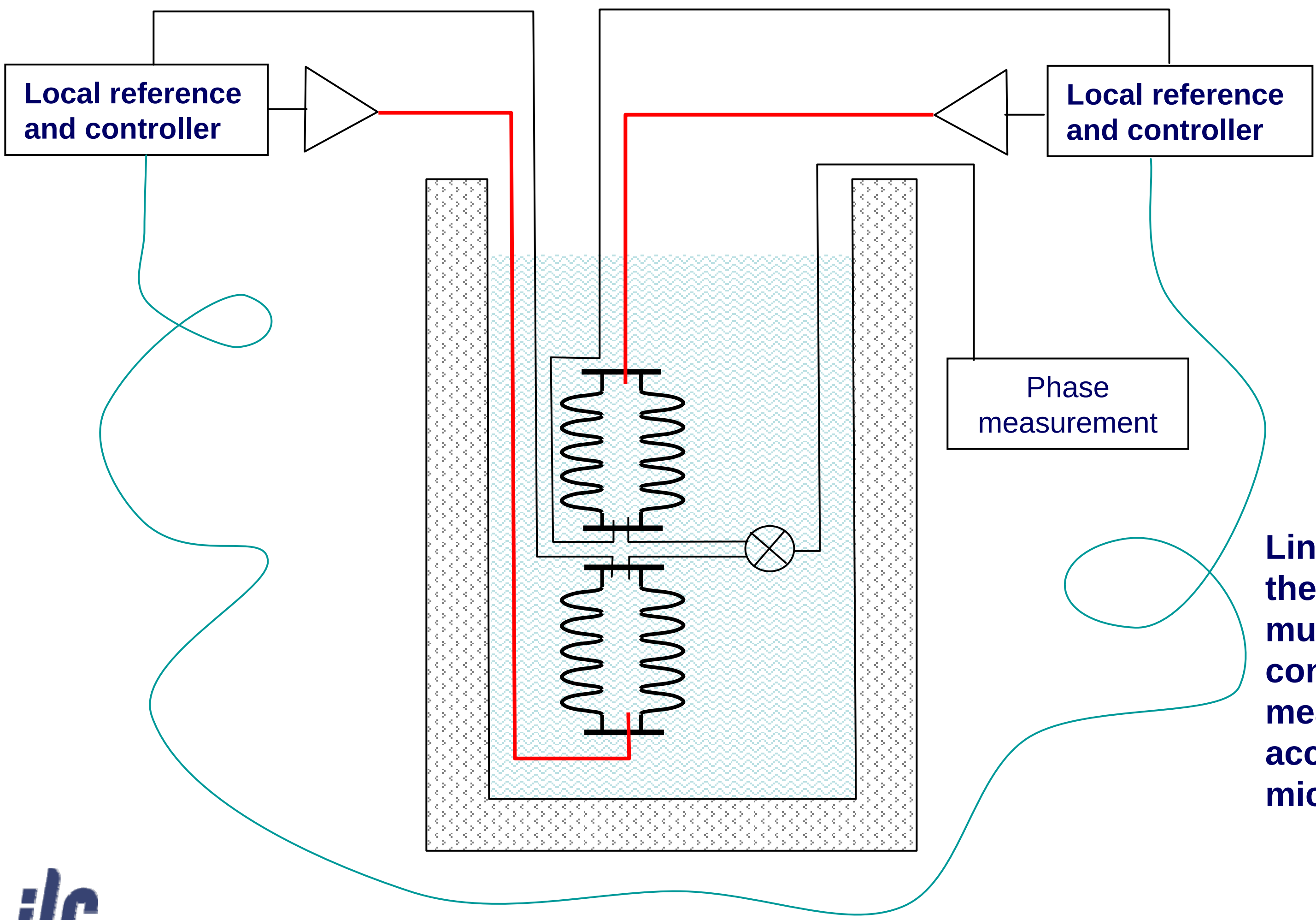


- If cavities are stabilized with respect to local references to ± 0.01 degrees we then seek synchronisation between local references to 0.06 degrees at 3.9 GHz = 43 fs
- Optical systems have been developed elsewhere that achieve this.
- Initial plans are to see what can be achieved with coax and s.o.a. RF components.



simple synchronisation scheme

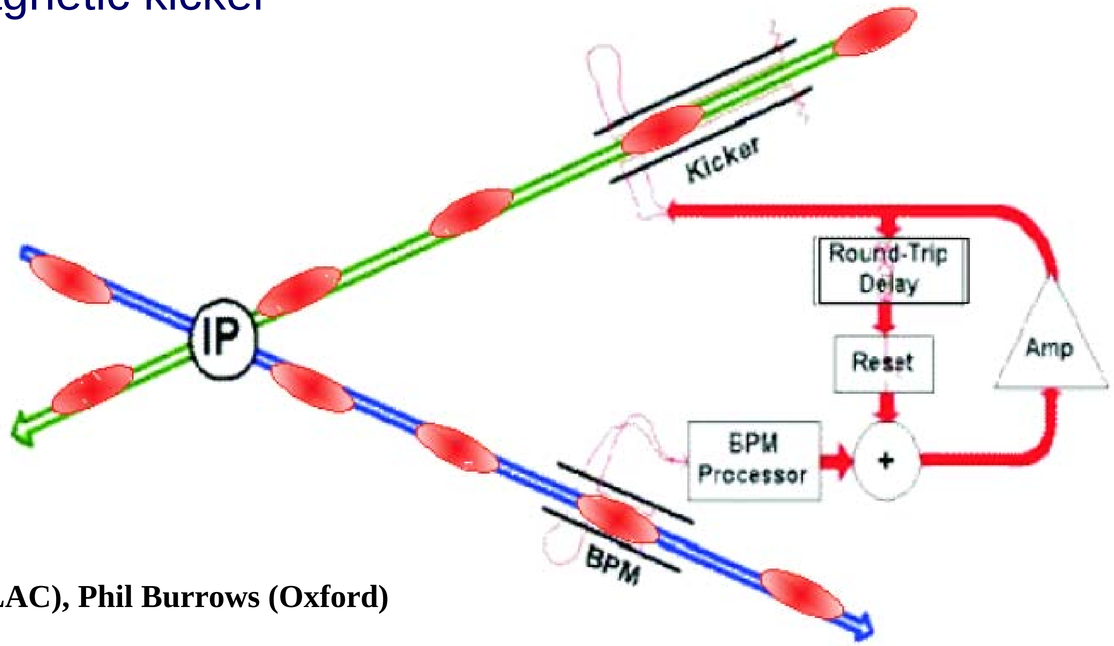
Vertical Cryostat Phase Control Tests



Line to synchronise the local references must have its length continuously measured to with an accuracy of a few microns

Horizontal FONT

- The alternative to absolute phase synchronisation is to using a horizontal FONT system.
- If one can accurately measure the x displacement of the spend beam (after the IP) as it passes the crab cavity on the ingoing beam one can determine the phase error between the crab cavities.
- The deflection can be cancelled either by changing the phase of one cavity or using a magnetic kicker



Chris Adolphson (SLAC), Phil Burrows (Oxford)

Work plan Status Goal 2

System design

No	Due	Task	Status
2.1	Apr 06	Study of crab cavity deflection mode effects on beam dynamics	**Complete**
2.2	Jul 06	Contribute to RDR	**Complete**
2.3	Jul 06	Study of effect of HOMs on beam dynamics (kick only – not emittance growth).	**Complete**
2.4	Oct 06	Development of RF system model (phase stability performance).	**Initial model available**
2.5	Feb 07	Recommendation on development of a superconducting crab cavity.	**Initial recommendations made**

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Work plan Status Goal 3

Cavity and RF Design and development

No	Due	Task	Status
3.1	May 06	Electromagnetic design of a multi-cell dipole superconducting cavity including couplers and system for damping higher order modes (HOMs).	**Using CKM 3.9 GHz– coupler development is needed..**
3.2	Aug 06	Numerical multipacting study for a multi-cell dipole cavity.	**Need coupler designs to complete**
3.3	Nov 06	Development of LOM damping of system and coupler design.	**Major collaboration task in progress – completion in 2007**
3.4	Jan 07	Manufacture and testing of normal conducting prototype cavity.	**Cavity manufactured and initial tests completed**
3.5	Nov 07	Full design recommendations with respect to electromagnetic design, electronic design and thermal design.	**Awaits other results**

Work plan Status Goal 4

Phase Stability Experiments

No	Due	Task	Status
4.2	Apr 06	Phase control measurements/experiments on ERLP defined	Complete
4.3	Jul 06	Phase control measurements/experiments on ERLP set up.	Postponed to 2007
4.5	Jan 07	Establish validity of phase control model.	Requires completion of 3.3 or other experiment
4.7	Jan 07	Phase performance tests complete.	Tests not reliant on ERLP are also being planned
4.8	Nov 07	Proposal for high power tests of crab cavity system.	Dependent on future funding program

4.1	Apr 06	Measurements of Klystron performance available.	Have some CPI data
4.4	Jul 06	Klystron performance simulation established.	Complete
4.6	Apr 07	Evaluation/development of phase control system.	On target
4.9	Jan 08	Final report on Klystron performance complete.	