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ILC Crab Cavity Collaboration

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EuroTeV Task CRABRF

Task description from pg.14 of proposal

design of high-power crab cavities • development of RF system model for phase stability performance • klystron design and performance studies • prototyping and low-power testing

Task milestones from pg.20 of Annex 1

36 months	**CRAB RF low-power systems test (inc. phase stability studies) available.**

Task milestones from pg.20 of Annex 1

Report on CRAB RF low-power prototype tests, including phase-stability system.

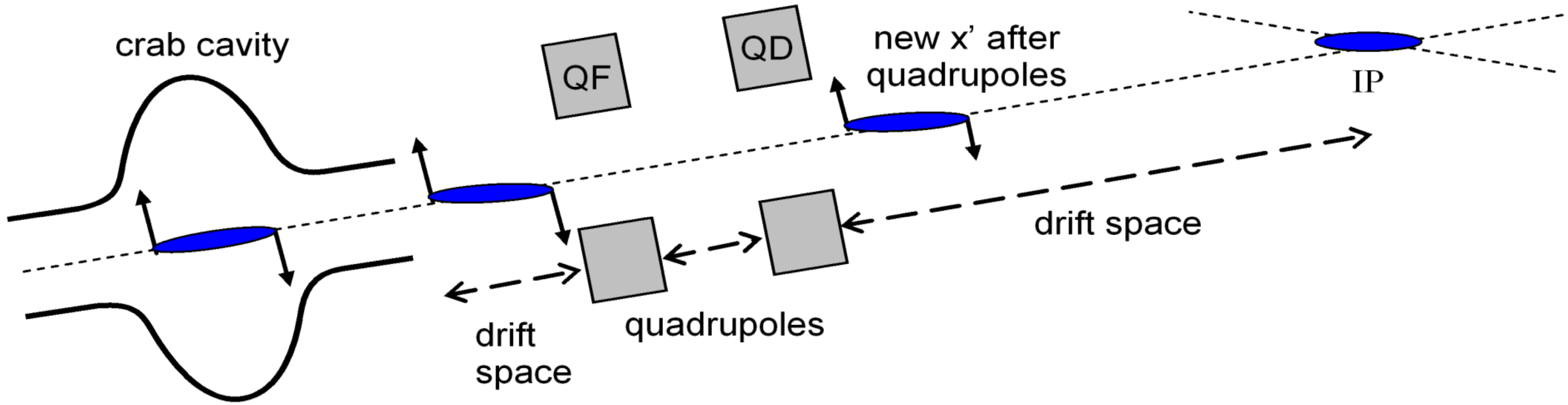
LC-ABD WP 5.2 combined with EuroTeV Subtask CRABRF

		Status	Notes
1.1	Study of crab cavity effects on beam dynamics.	Complete	
1.2	Establish crab cavity requirement	Complete	
1.3	Study of effect of HOMs on beam dynamics.	Complete	
1.4	Development of RF system model	Complete	
1.5	Recommendation on development of s.c. cavity	Complete	
2.1	Electromagnetic design of a multi-cell dipole s.c.	Complete	
2.2	Numerical multipacting study	Complete	Performed by SLAC
2.3	Dev. LOM damping system and coupler design	Complete	
2.4	Manu./testing of a normal conducting prototype	Complete	
2.5	Full design recommendations	Complete	As required by RDR
3.1	Measurement of Klystron/IOT perf. available.	Complete	EuroTeV
3.2	Phase control meas/exps on ERLP defined.	Complete	
3.3	Phase control meas/exps on ERLP setup.	Apr 08	ERLP was delayed
3.4	Klystron/IOT performance simulation established	Complete	EuroTeV
3.5	Establish validity of phase control model	Apr 08	Depends on 3.7
3.6	Evaluation/development of phase control system	Jan 08	EuroTeV
3.7	Phase performance tests complete	Apr 08	New test needs SRF infrastructure
3.8	Proposal for high power test of crab system	Complete	
3.9	Final report on Klystron/IOT perf. complete	Mar 08	EuroTeV (Extended)

Recent Crab Cavity Activities

ILC cavity wakefield analysis	Paper accepted IEEE Trans. Nuc. Sci.
ILC cavity coupler design	Measurements and modelling in progress
ILC cavity active damping of SOM	Experiments on ERLP planned
ILC cavity alignment	Report in preparation
ILC cavity measurements	Bead-pull and stretched wire on going
ILC LLRF cavity control circuits	New digital system ready for testing
ILC cavity control model	Preliminary results published at PAC07
ILC interferometer circuits	Dedicated boards being designed
ILC interferometer model	S Matrix model now available
Klystron transient modelling	Klystron at Lancaster Commissioned
CLIC Crab Cavity TW Design	RA appointment due 1st Feb 2008

Crab Cavity Function



The crab cavity is a deflection cavity operated with a 90° 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.

Technology Choice

CKM Cavity design parameters

3.9 GHz

13 cells   length = 0.5 m

B_{max} = 80 mT

E_{max} = 18.6 MV/m

L_{eff} = 0.5 m

$P_{\perp}$ = 5 M V/m

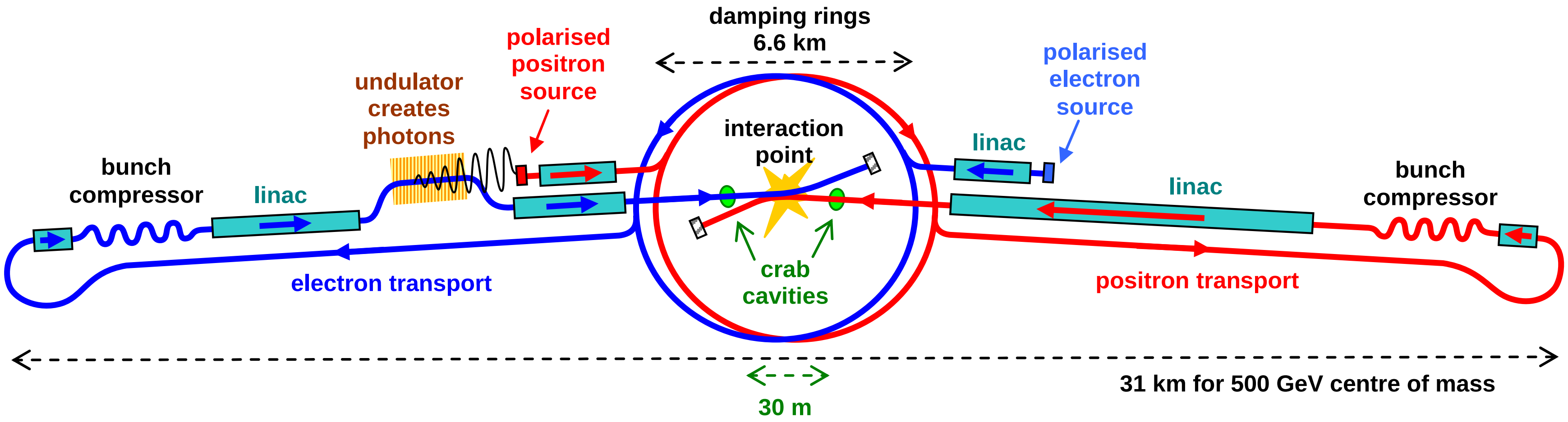
Courtesy: FNAL

Our recommendation to the GDE has been to develop a cavity based on a Fermi-lab design.

To minimise wakefields for the short time structure of the ILC bunches, the number of cells must be optimised against overall length and new couplers designed.

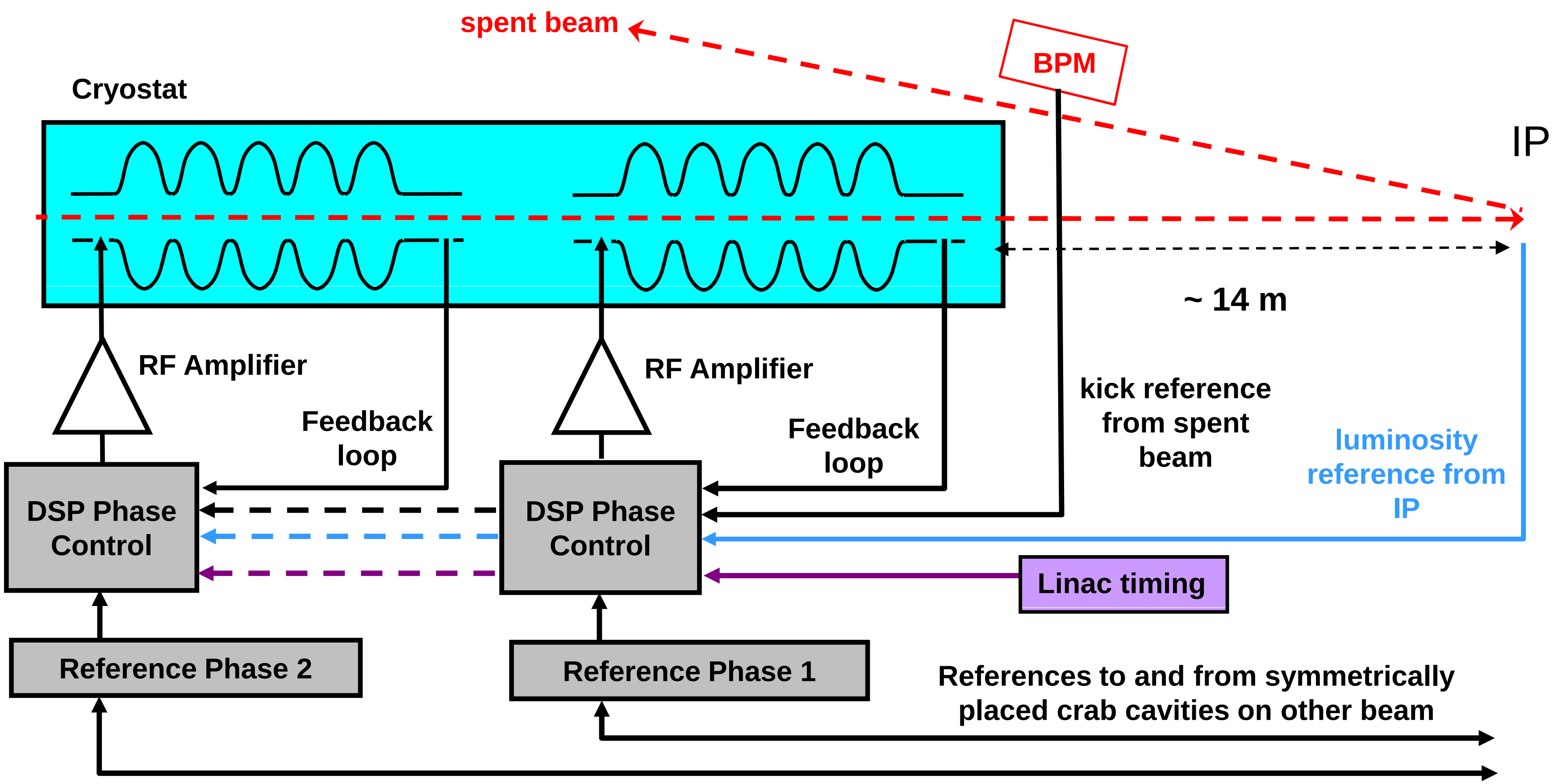
A 3.9 GHz cavity was favoured it is compact longitudinally and transversely.

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 80%.

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…

Consequential Timing Requirements

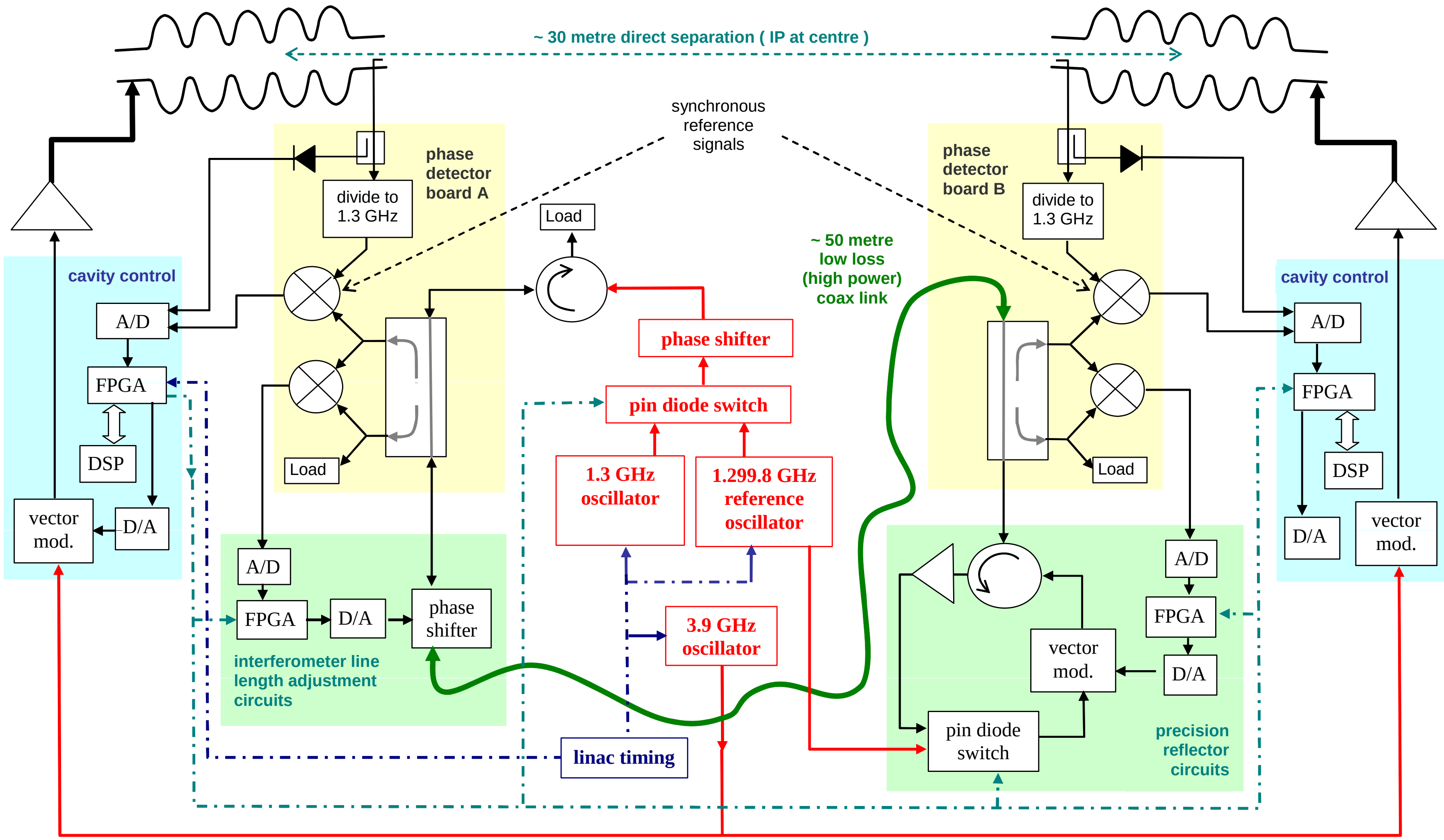
The timing budget might be considered as three equal uncorrelated parts given as 90 fs / √3 =51 fs (= 72 milli degrees at 3.9 GHz)

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.
- 51 fs corresponds to 15 μm hence if the synchronisation is to be by dead reckoning then 15 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.

Planned Scheme expected ~ 2010



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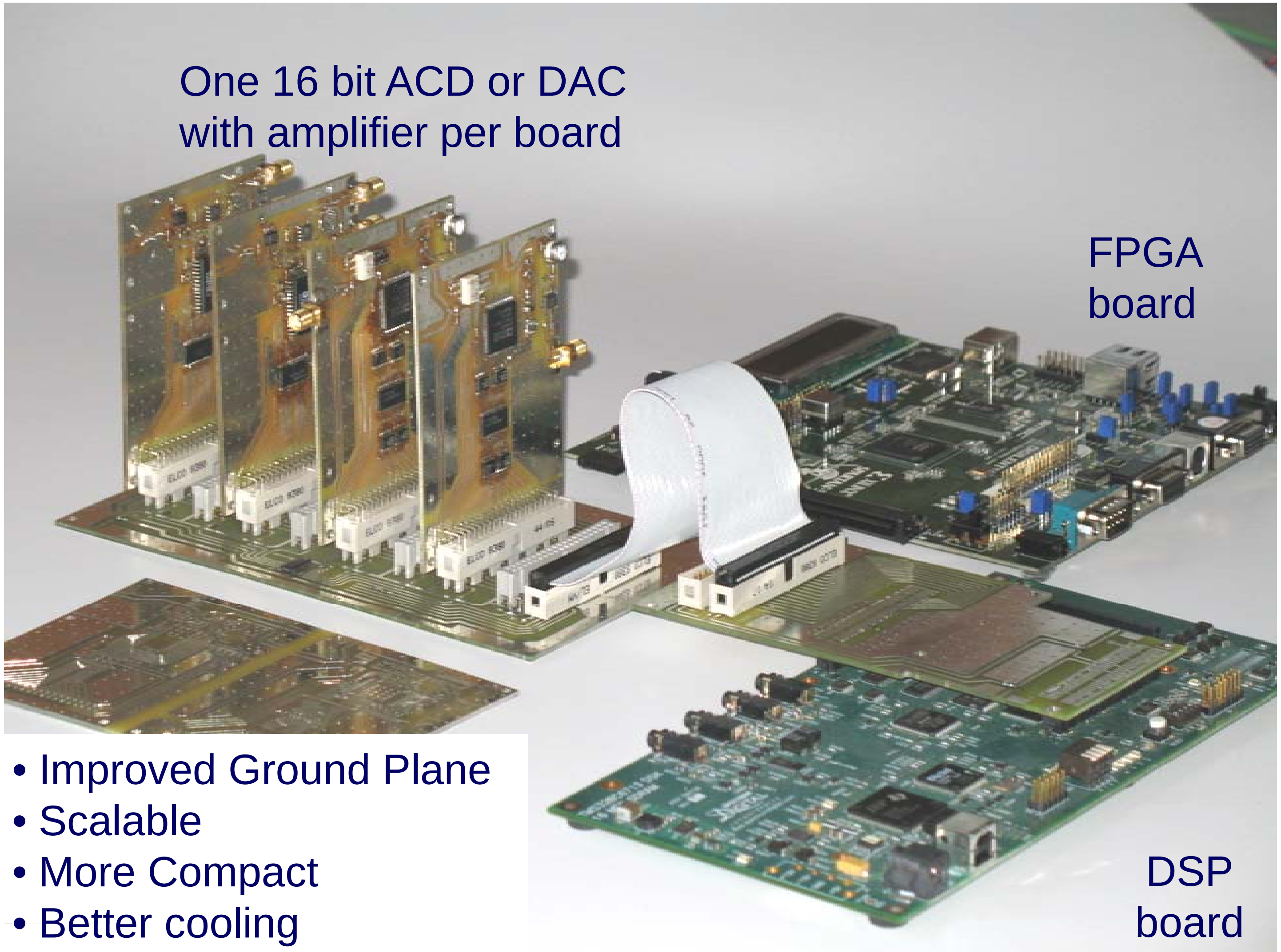
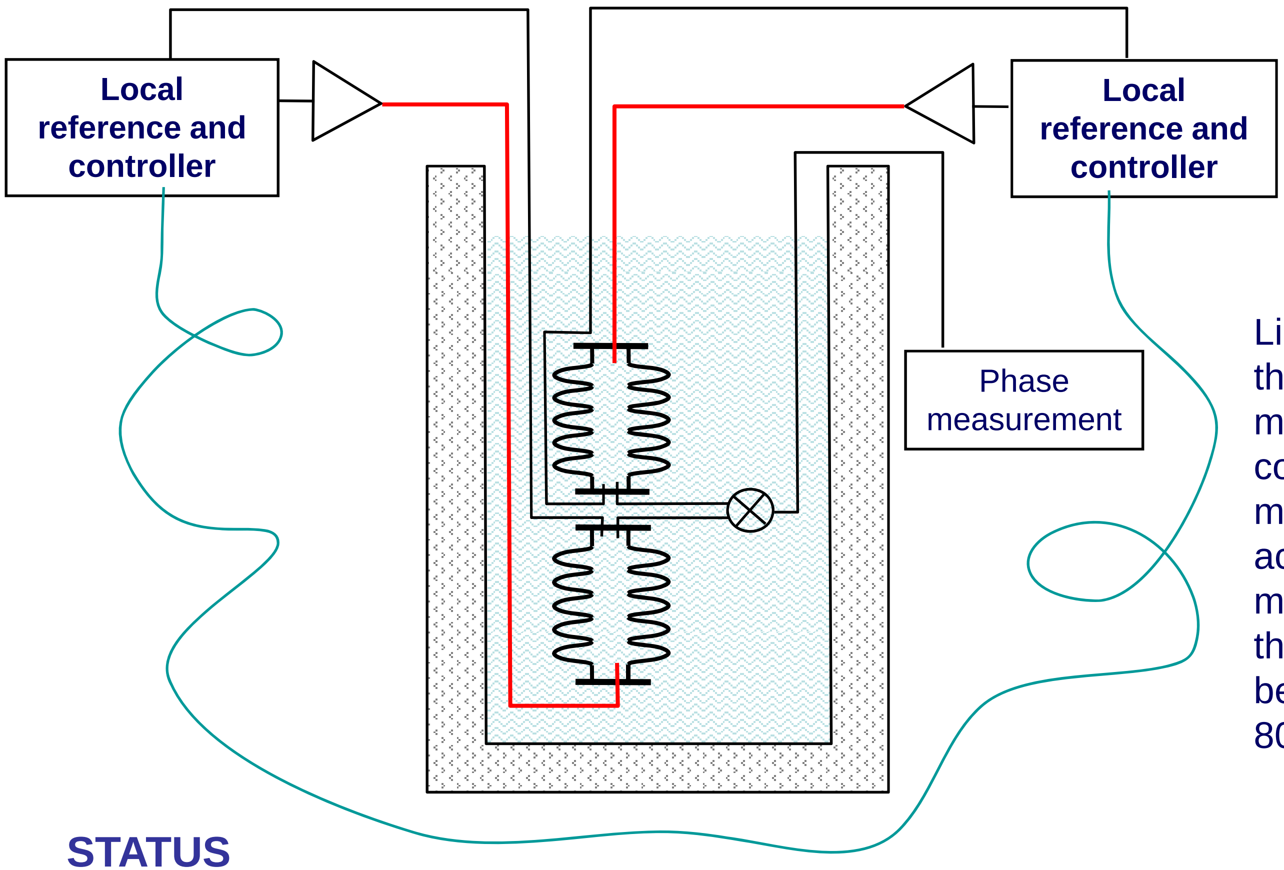
ASTeC

New ADC and DAC Modules



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

Vertical Cryostat Phase Control Tests

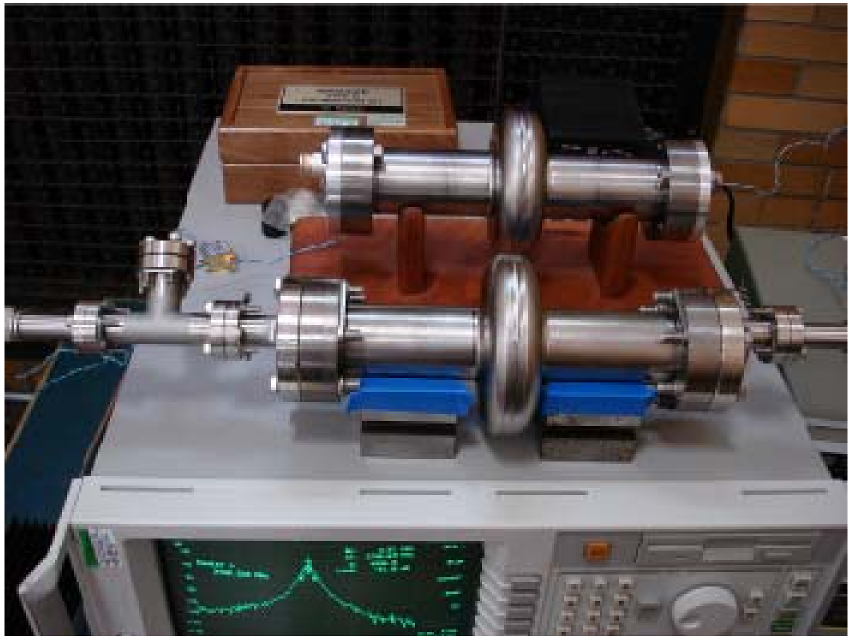


Line to synchronise the local references must have its length continuously measured to with an accuracy of a few microns. On the ILC this line is likely to be between 50m and 80m in length.

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.

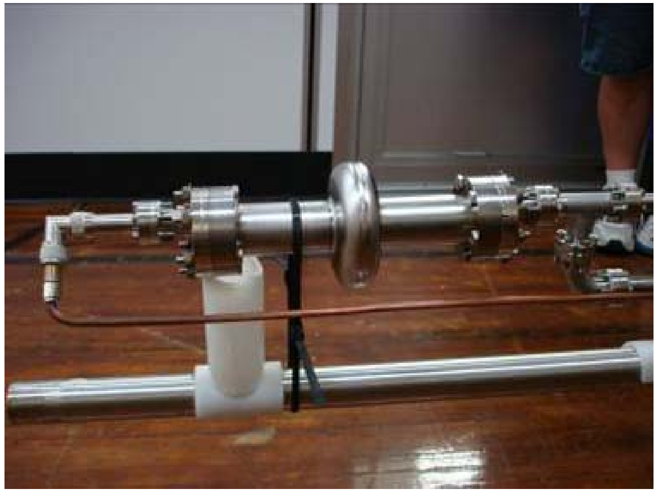
Single Cell Processing

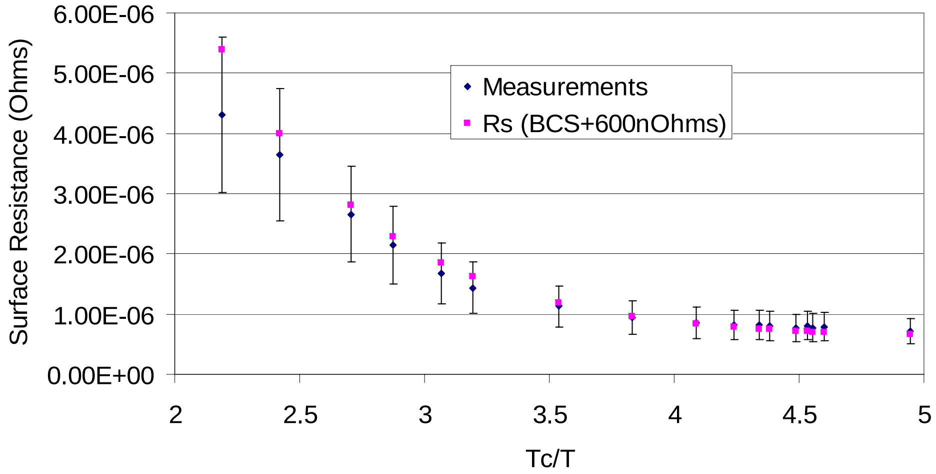


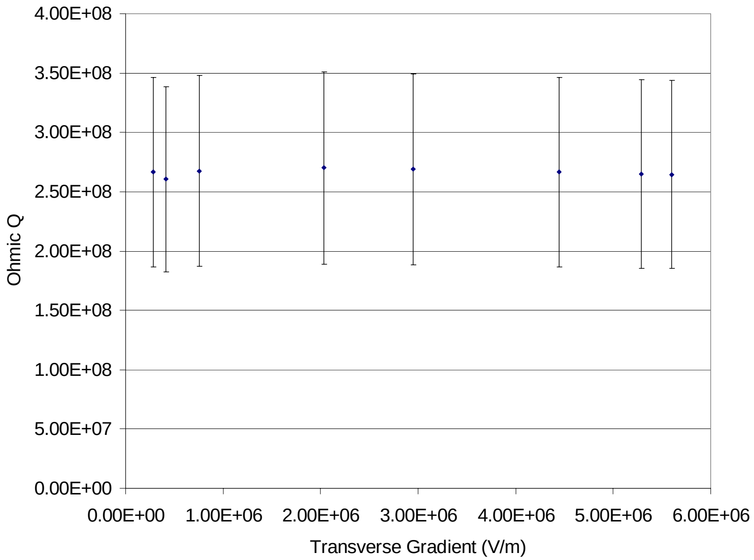
Three SCRF single cell cavities have been constructed for the phase control tests due Jan 08. Their manufacture has allowed transfer of key SCRF skills and know how to the STFC Daresbury.

Cavities were given a 150 micron Buffered Chemical Polish and a 20 minute High Pressure Rinse.

Single Cell Tests







The cavities had a relatively large residual resistance. The losses are acceptable for the phase control tests but are too large for the ILC. The cavities achieved the required gradient without quench.

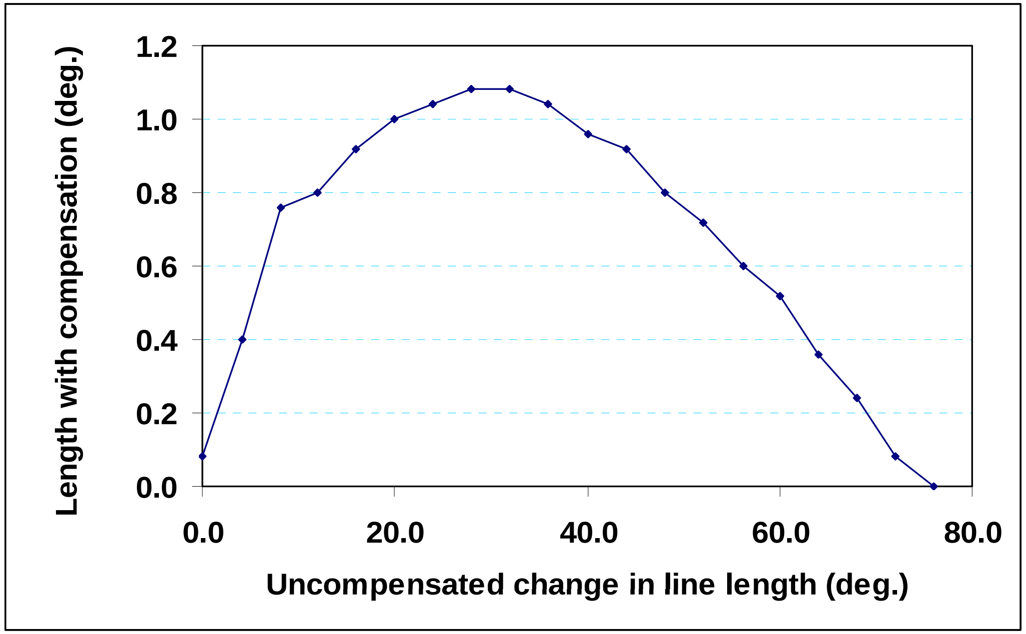
Current Interferometer Results

Anticipated length change on the actual interferometer cable ~ 20 ppm

Length change = 1 mm for a 50 m cable giving 1.6 degrees phase shift at 1.3 GHz

The interferometer is being tested without the crab cavities and line length is varied with a manual phase shifter.

Residual error from unwanted reflection must be measured and eliminated by applying an appropriate correction. In the final system amplitude modulation will allow corrections to be determined automatically while the system is running.

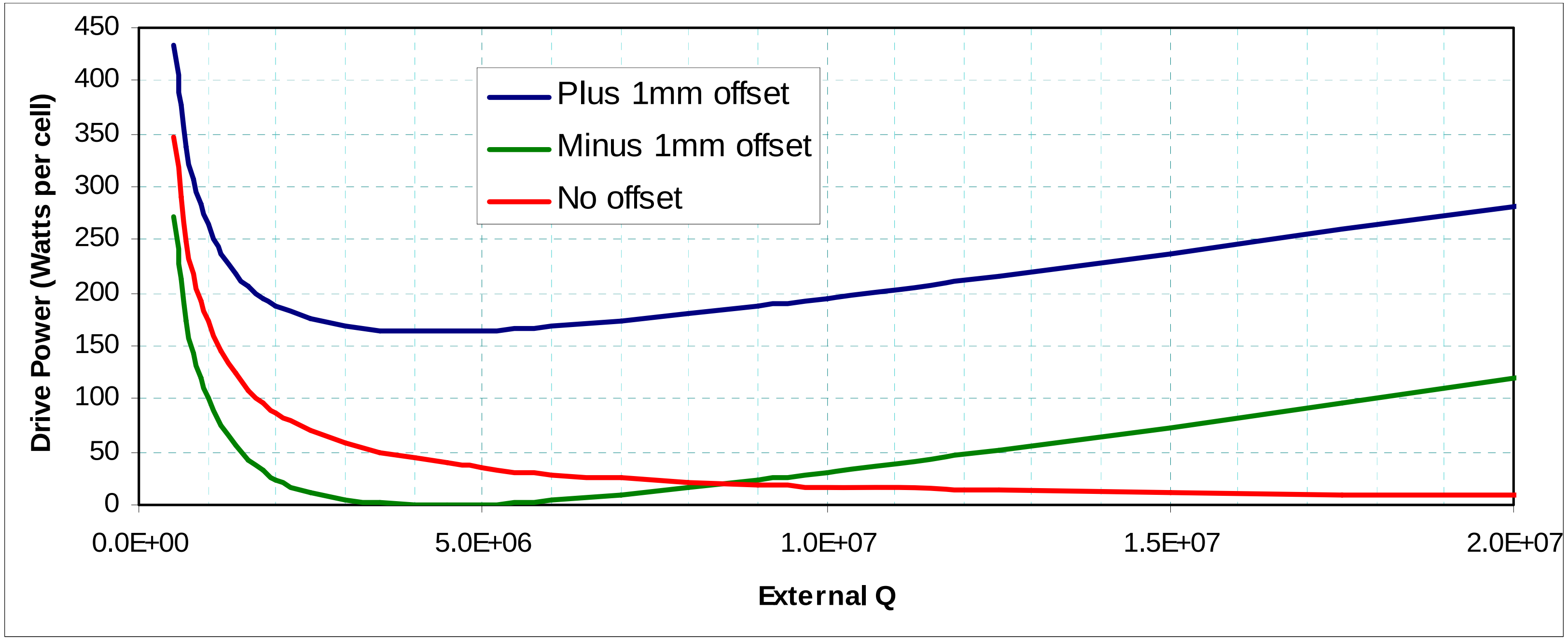


The loop filter and phase shifter compensate the change in length. Perfect compensation would give a horizontal line. Where reflections on the line cancel, (near to 30^o in this case) compensation is excellent.

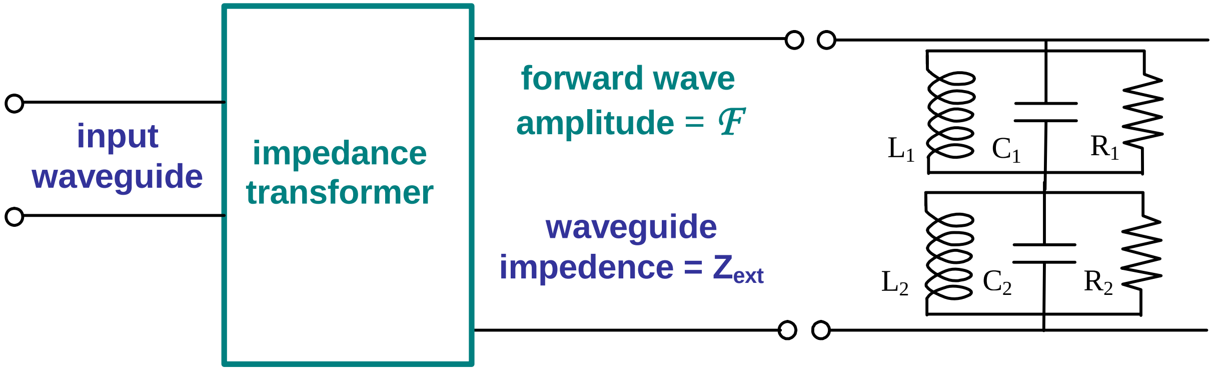
Jitter for the initial system was 7 milli-degrees r.m.s. at 1.3 GHz for a 200 kHz bandwidth.

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

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

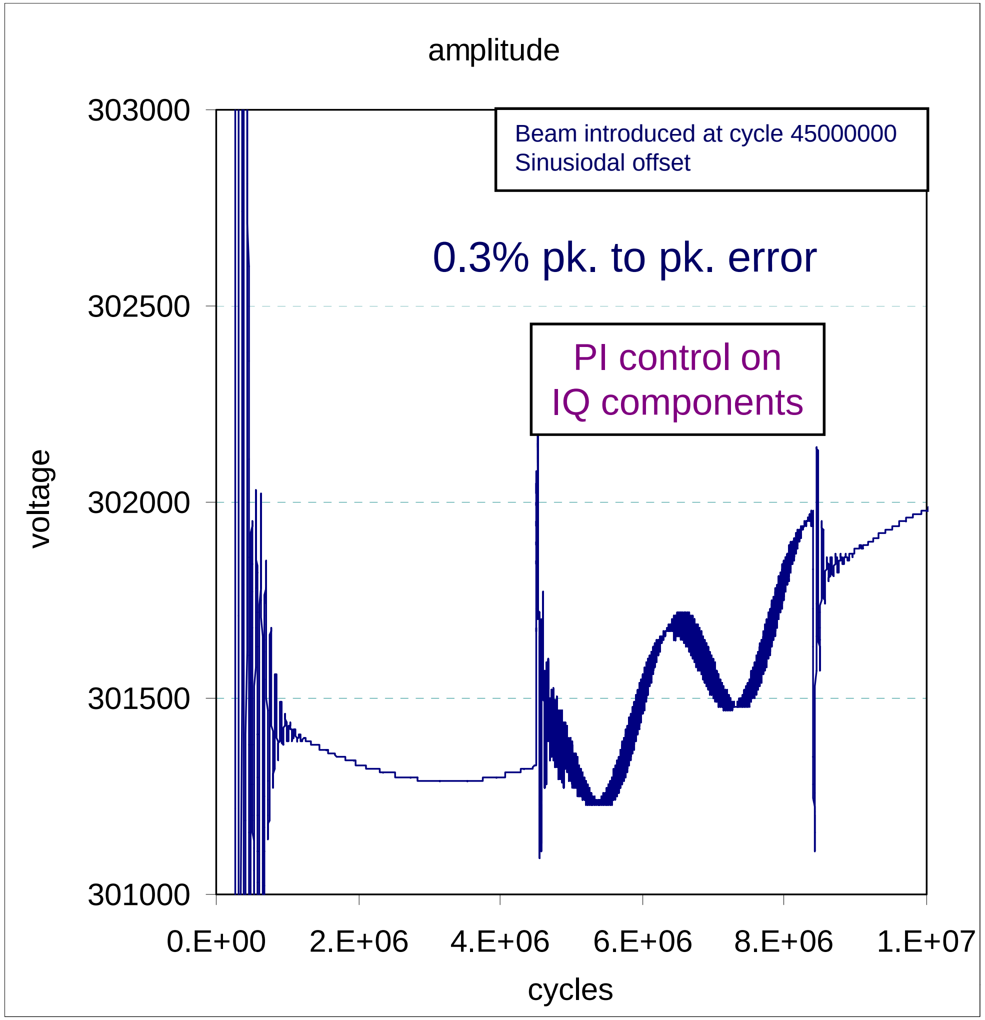
conversion from circuit parameters to cavity parameters

- 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

Amplitude Control

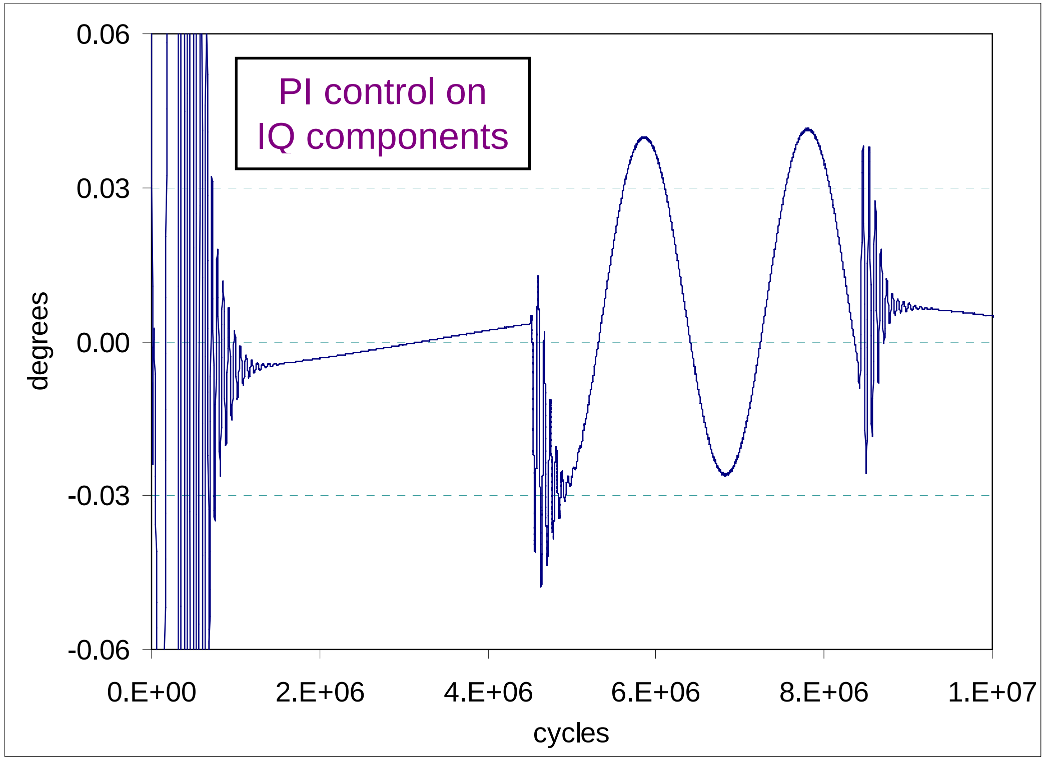
Bunch train introduced after 4.5e5 cycles with 0.6 mm oscillating offset.
No measurement errors included in this calculation (see later for measurement errors).



Drive frequency in GHz	= 3.900 GHz
Centre cavity frequency in GHz	= 3.900 GHz
Number of cavity modes	= 3
Cavity Q factor	= 1.0 E+09
External Q factor	= 3.0E+06
Cavity R over Q (2xFNAL=53 per cell)	= 53.000 ohms
Energy point ILC crab~0.0284J per cell)	= 28.400 mJ
Amplitude set point	= 301.675 kV
Maximum Amplifier Power per cell	= 1200.0 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	= 12000
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)	= 0.0 deg
Fractional err in amplitude measurement	= 0.0
Time delay (latency) for control system	= 1.0E-06 s
Control update interval	= 1.0E-06 s
Gain constant for controller	= 0.7000
Amplifier bandwidth	= 1.0E+07
Measurement filter bandwidth	= 5.0E+05
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	= 4.2000E+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

Phase Control



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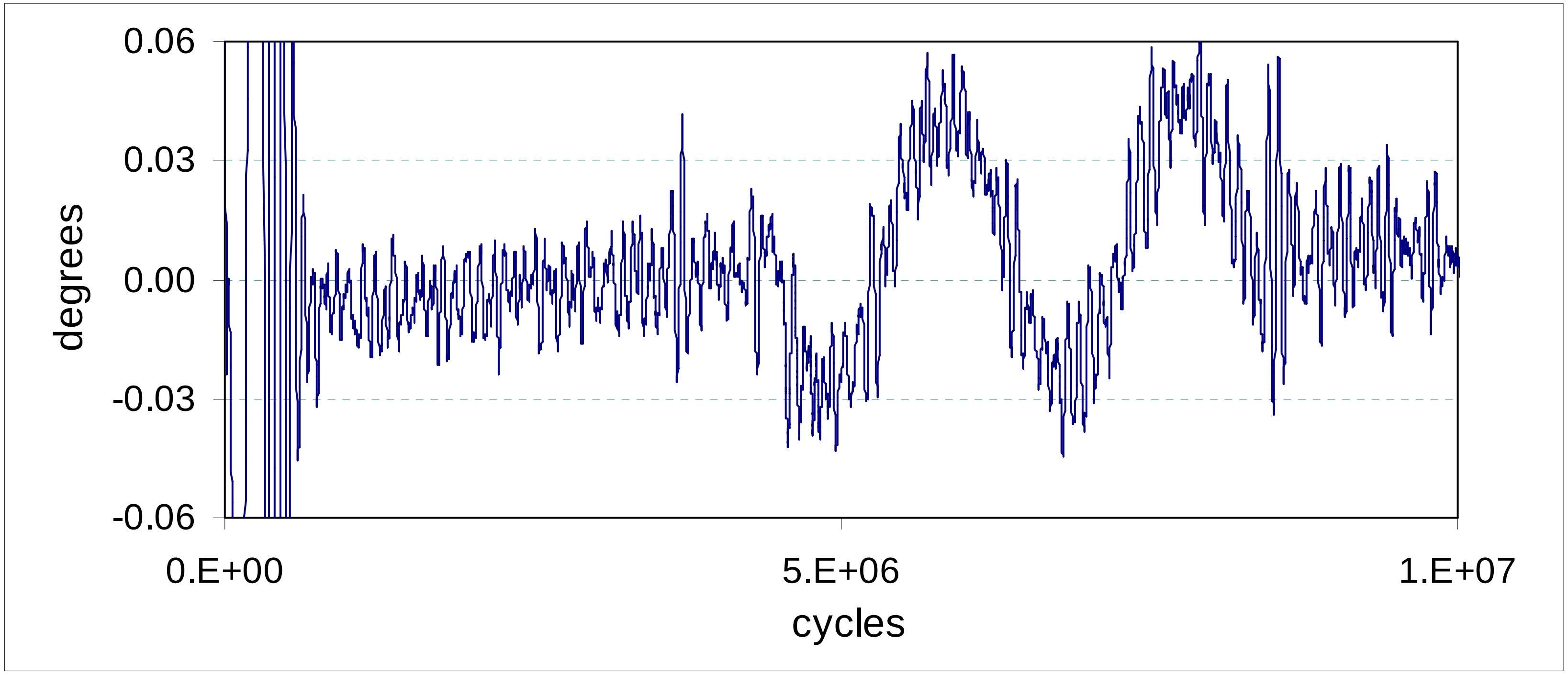
Integral coef for real component	=	1.2600E-03
Proportional coef for imag component	=	4.2000E+01
Integral coef for imag component	=	1.2600E-03

- No measurement errors included
- Three modes included (π , π-1 , π-2)
- 0.6 mm oscillating beam offset
- 712 fs random, bunch timing errors
- Control loop latency ~ 1 μs (difficult to achieve)
- Fast oscillation follows beamload (0.6 mm oscil.)
- Slow oscillation follows microphonics

Phase control with measurement error

Parameters as before but – with +/- 0.1% amplitude errors
and random phase measurement error of +/- 0.015 degrees
(The controller filters the measurement signal appropriately)



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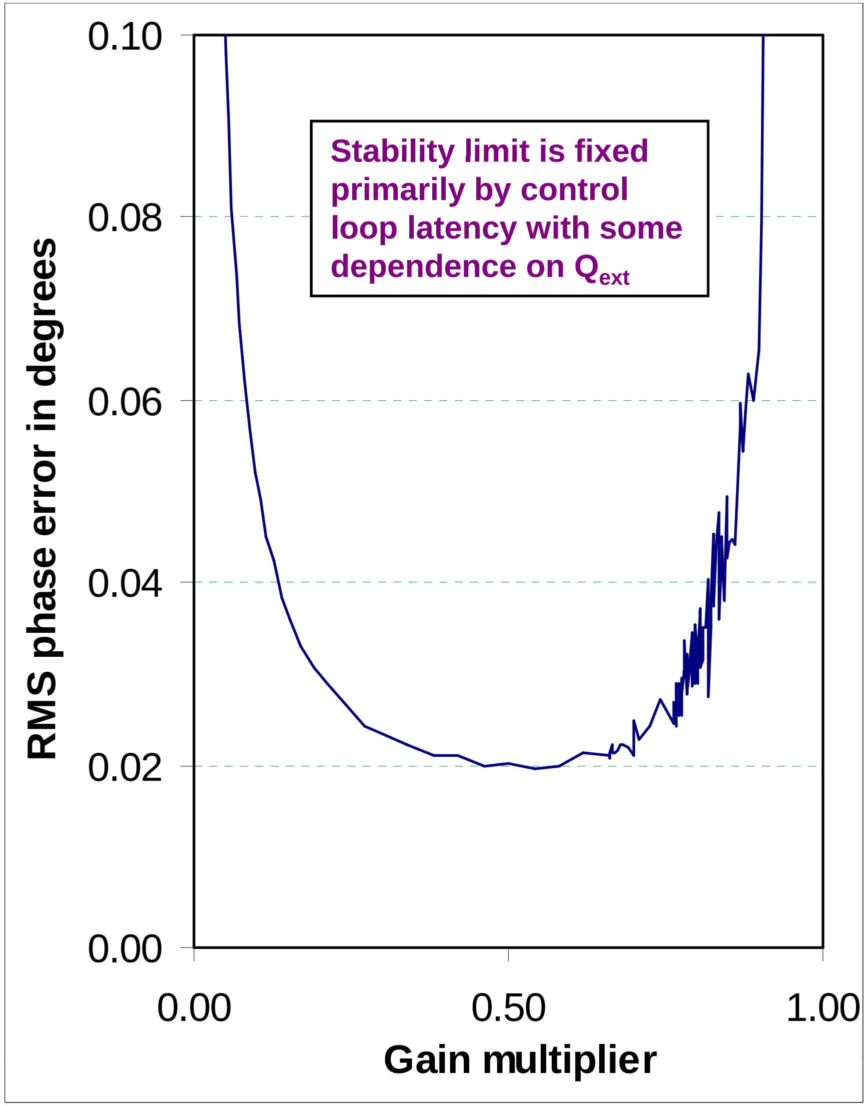
Performance verses gain



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Maximum voltage set point (no beam)	= 1235.476 kV
Maximum beam offset	= 0.600 mm
Maximum bunch phase jitter	= 1.000 deg
Beam offset frequency	= 2000.000 Hz
Bunch charge (ILC=3.2 nC)	= 3.200 nC
RF cycles between bunches	= 1200.000
Bunch train length	= 1.000 ms
Cavity frequency shift from microphonics	= 600.000 Hz
Cavity vibration frequency	= 230.000 Hz
Initial vibration phase (degrees)	= 20.000 deg
Phase measurement error(degrees)	= 0.01500 deg
Fractional err in amplitude measurement	= 0.00100
Time delay (latency) for control system	= 1.0000E-06 s
Control update interval	= 1.0000E-06 s
Start gain constant for controller	= 0.0050
Amplifier bandwidth	= 1.0000E+07
Measurement filter bandwidth	= 5.0000E+05
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

Cavity Phase Control Summary

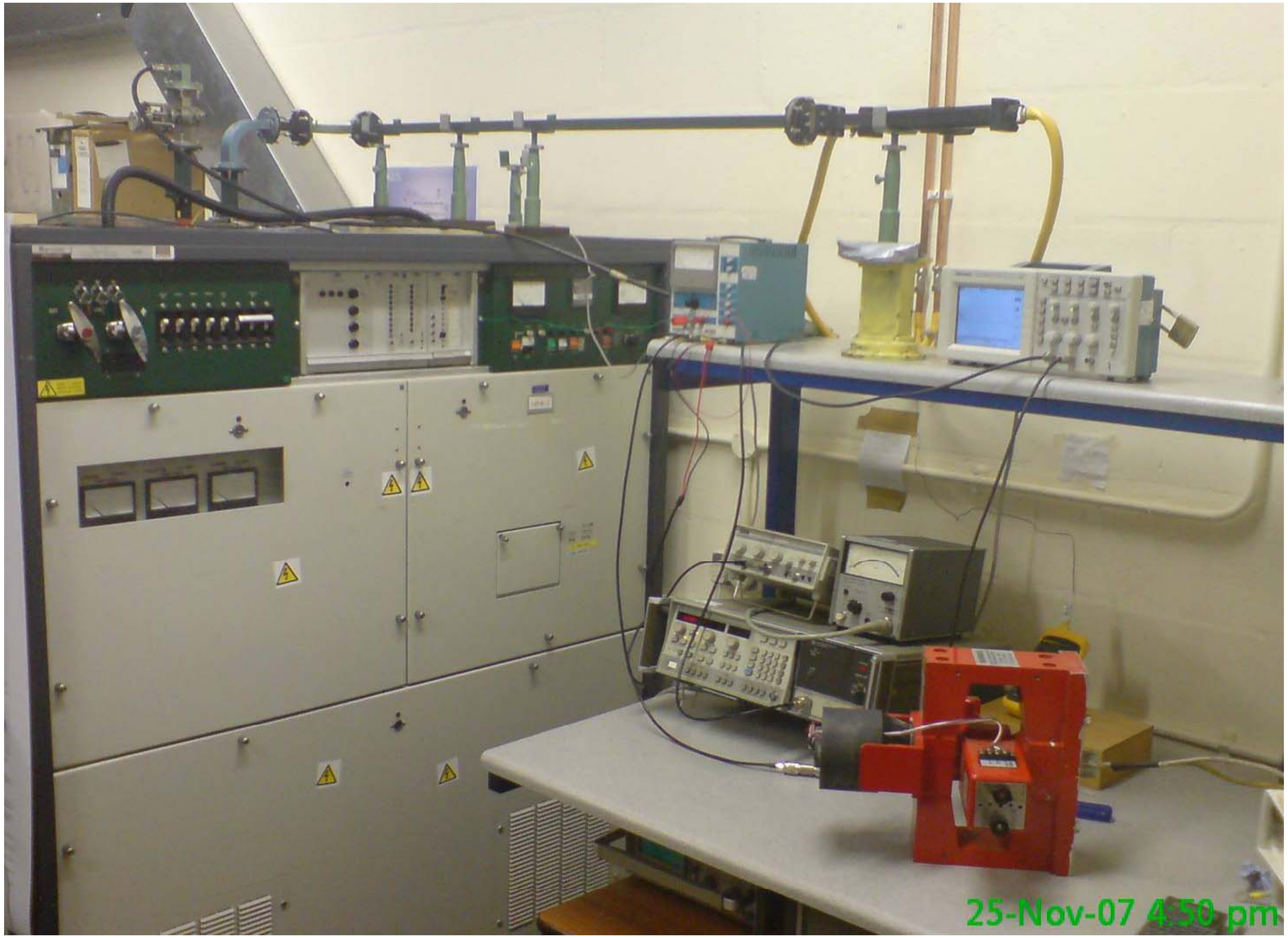
Phase stability performance has been modelled for

- anticipated beam jitter
- levels of microphonics observed in the FNAL CKM cavity
- measurement errors typical for digital phase detectors
- an ambitious latency of 1μs
- Q external optimised for power transfer
- with two adjacent modes

RMS cavity phase jitter at optimum gain was 0.03 degrees

This is within the budget of 0.072 degrees.

Klystron Performance Measurements



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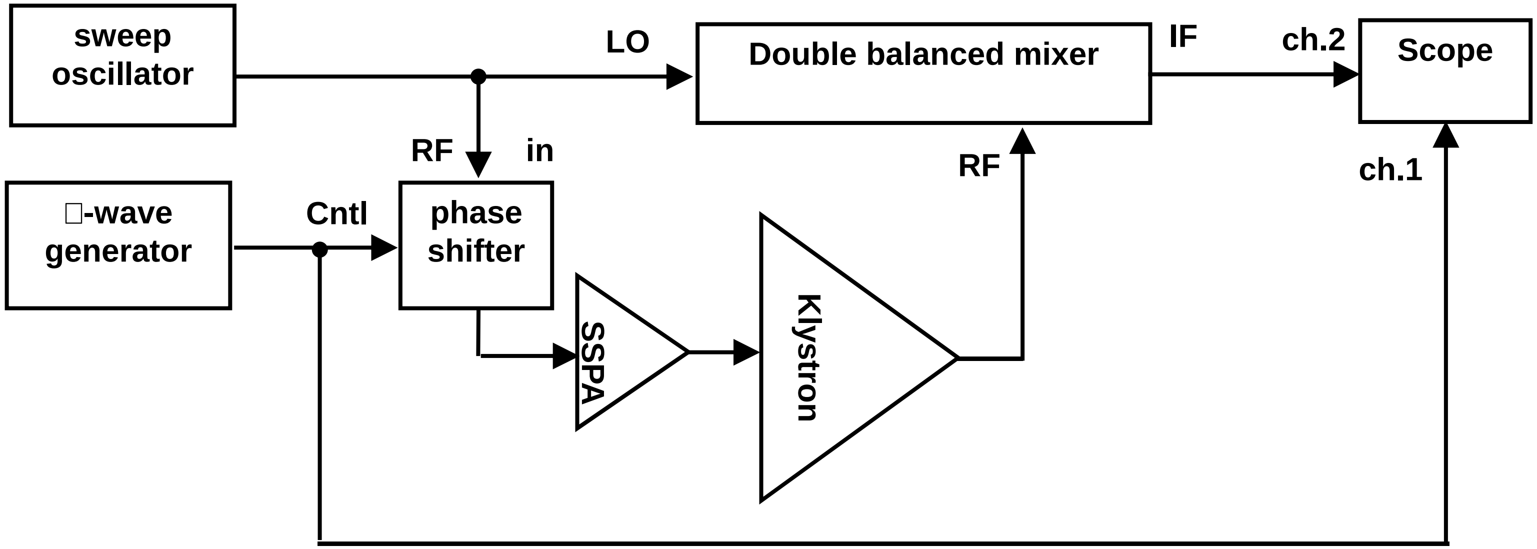
TH2450 klystron

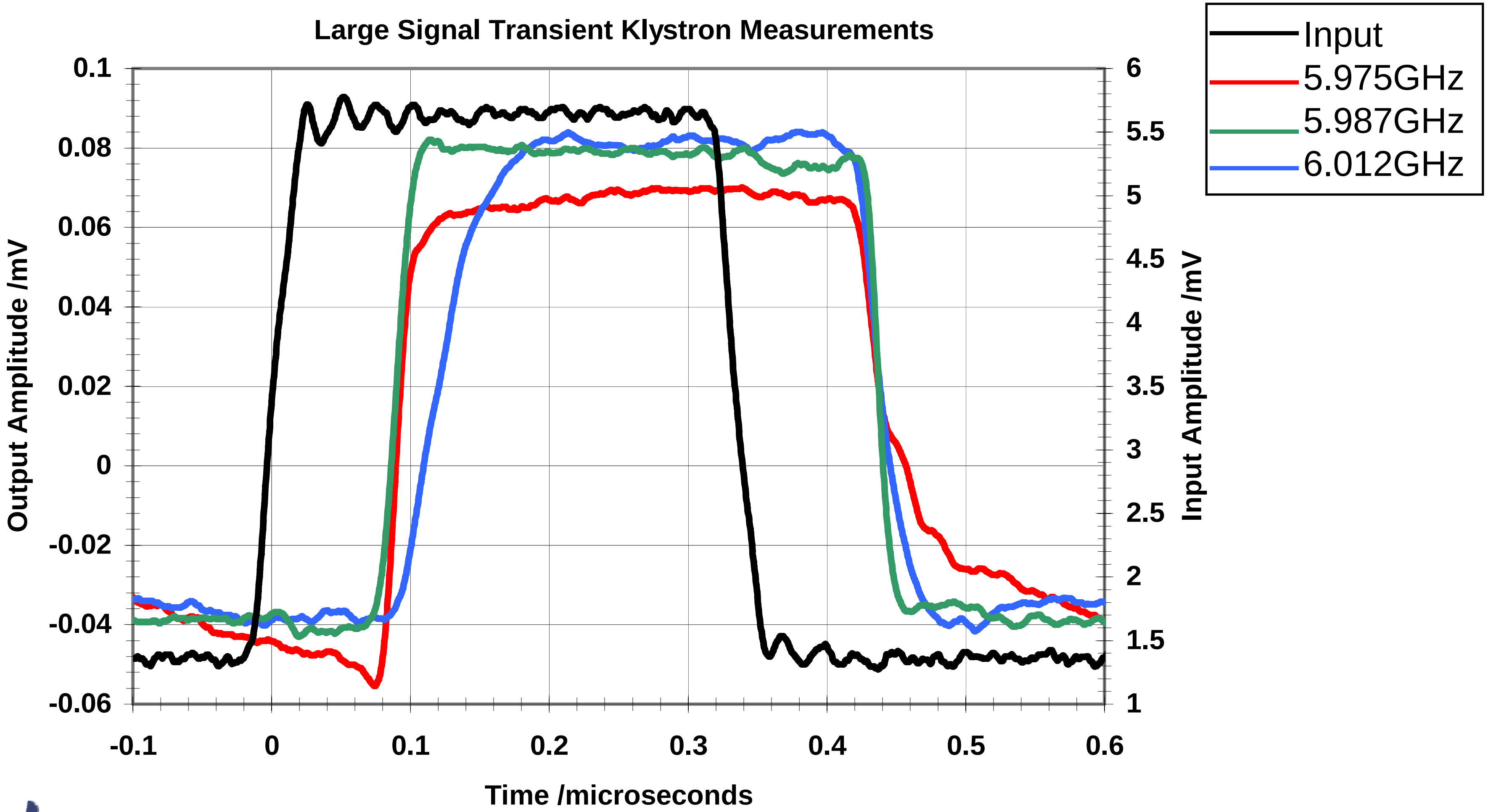
international linear collider

Fermilab

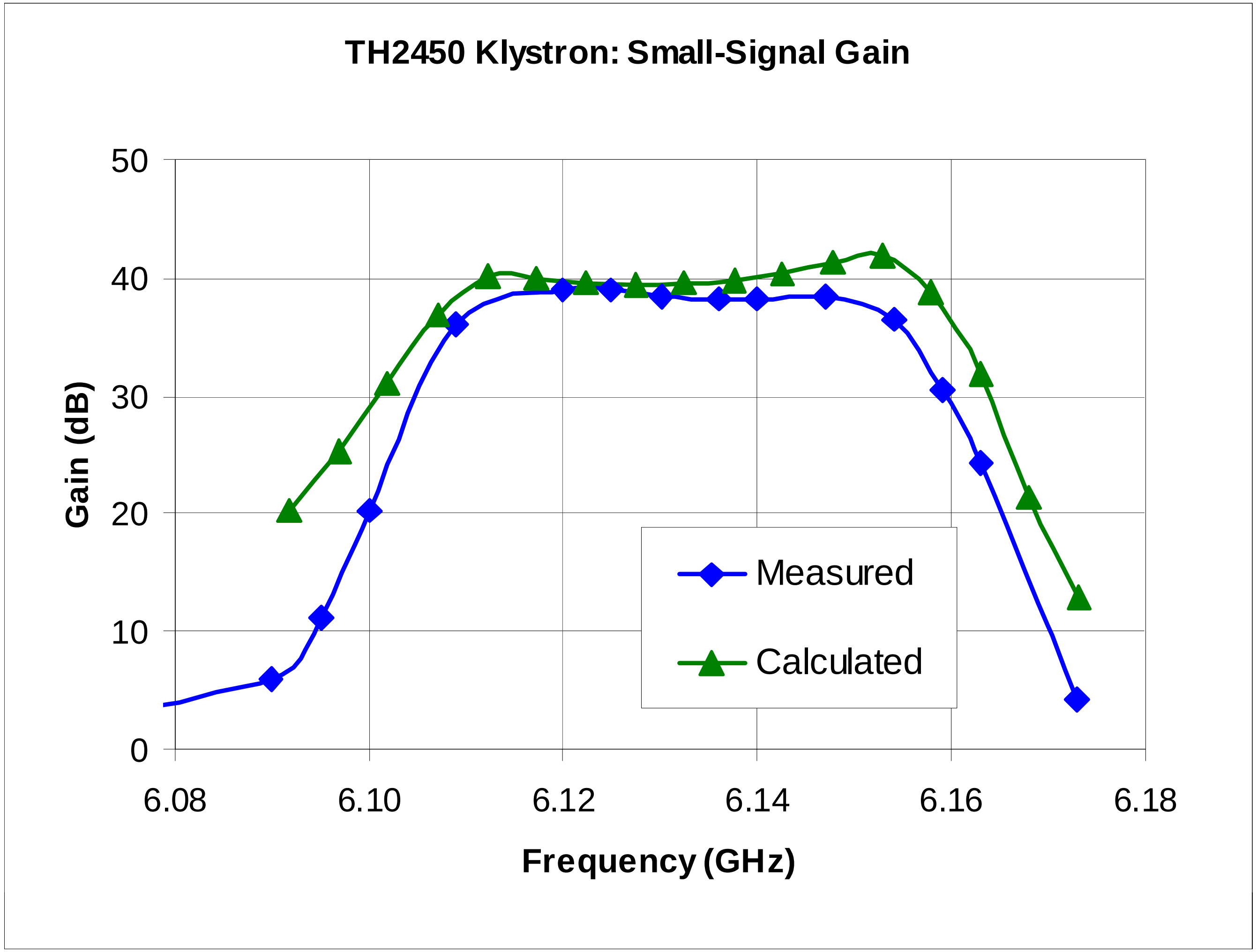
Schematic Setup for Klystron measurements



Klystron Transient Response Measurements



Small-signal gain



Damping Requirements

If the bunch repetition rate is an exact multiple of the unwanted modal frequency the induced wakefield has a phase such that it does not kick the beam. Maximum unwanted kick occurs for a specific frequency offset. This value must be used to determine damping.

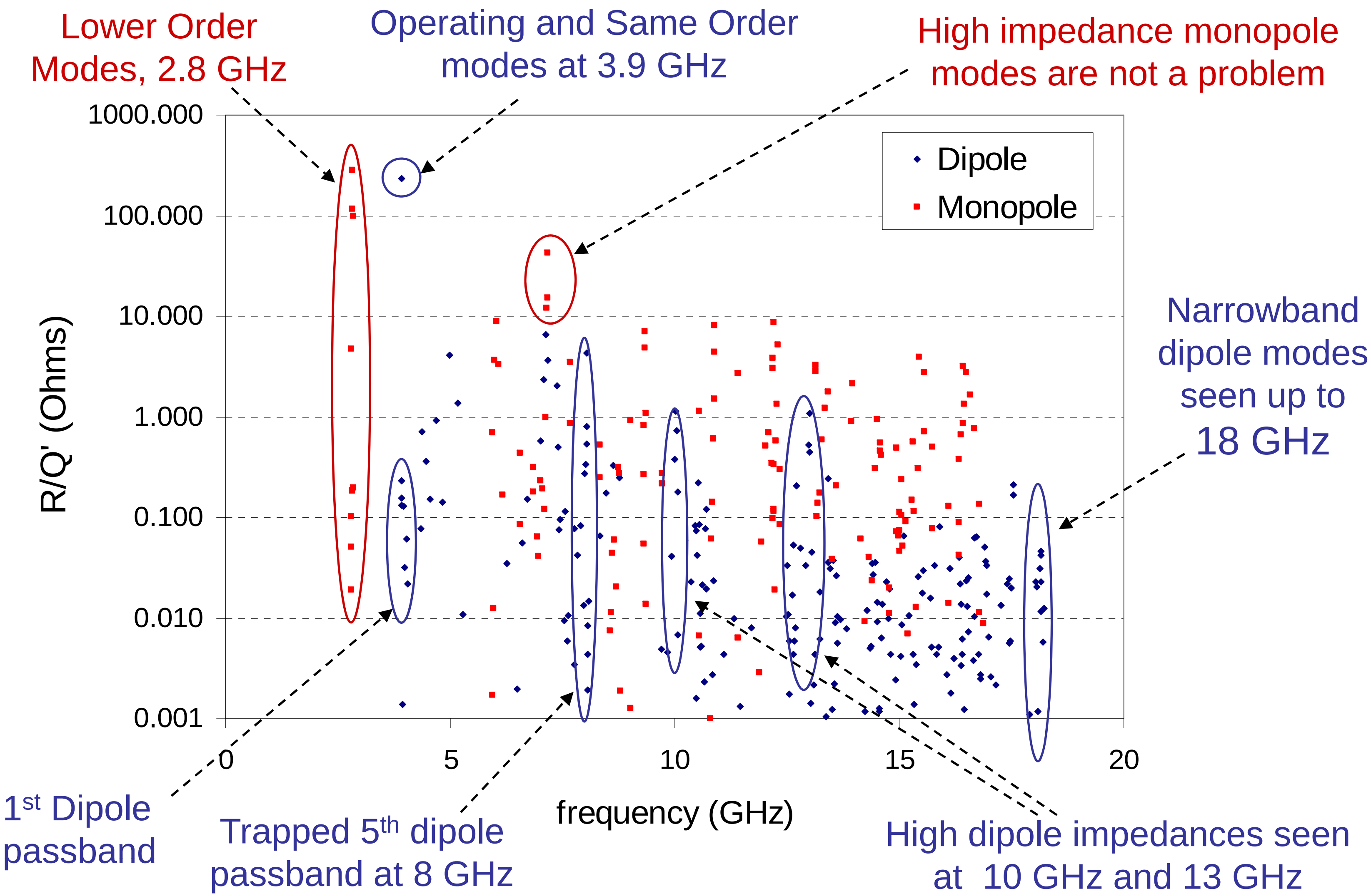
For each unwanted mode determine the required external Q factor using

$$Q_{ext}(m) = \frac{\omega_m t_b}{2} \operatorname{cosech}^{-1}\left\{ \frac{4\,\Delta y_{ip} E}{q\, c\, r_{off}\; R_{12} \left(\frac{R}{Q}\right)_m} \right\}$$

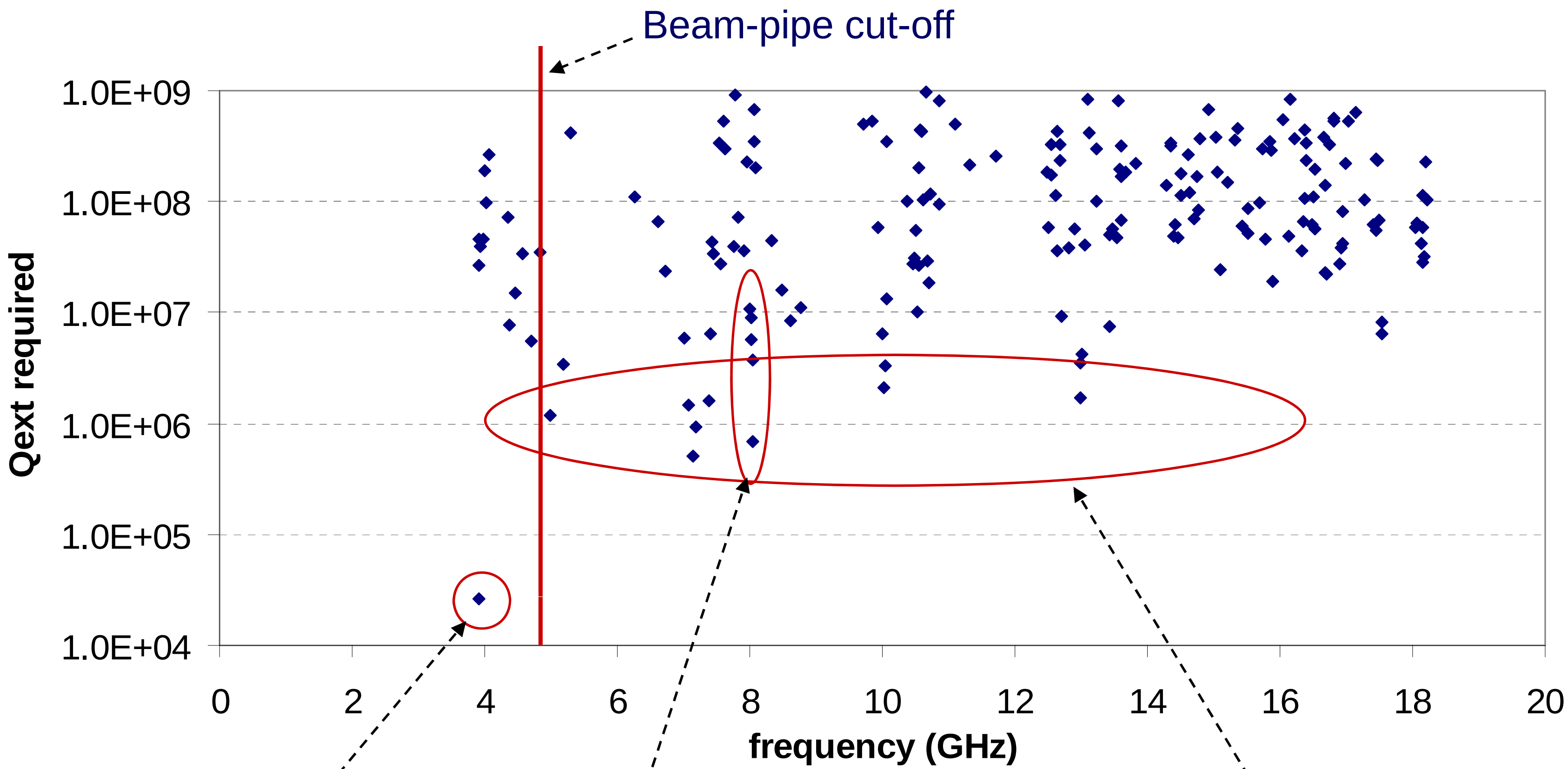
m = mode
ω_m = mode freq.
t_b = bunch spacing
q = bunch charge
r_{off} = max bunch offset
E = bunch energy
Δy_{ip} = max ip offset
c = vel. light

G. Burt, R.M. Jones, A. Dexter, "Analysis of Damping Requirements for Dipole Wake-Fields in RF Crab Cavities." IEEE Transactions on Nuclear Science, Vol 54, No 5, pp 1728-1734, October 2007

Modal Calculations in MAFIA



External Q factor s required for couplers

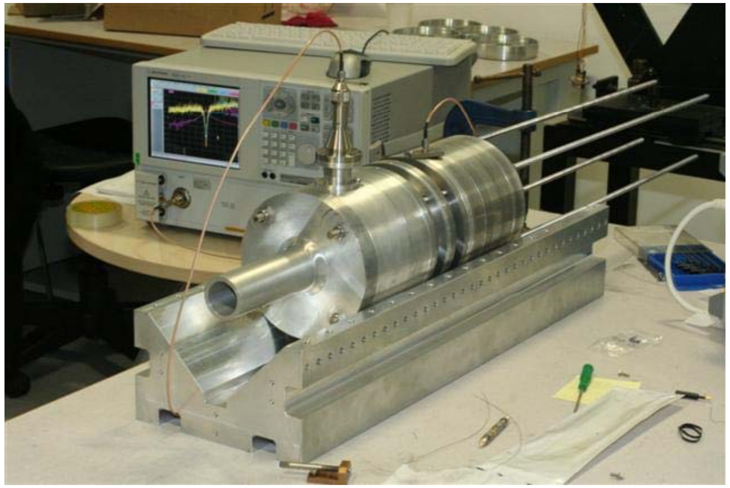


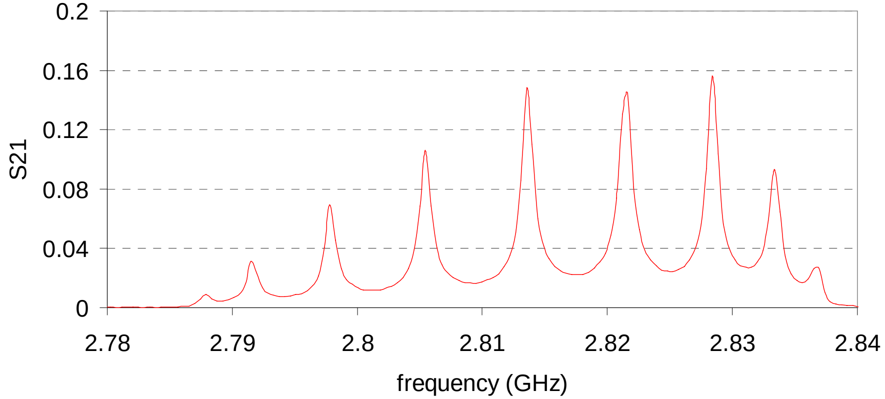
Same Order Mode, tough spec, requires active damping

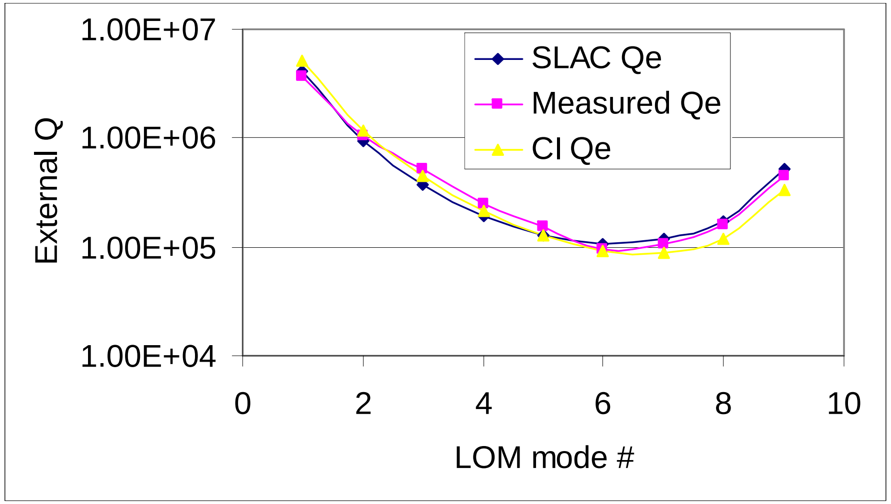
Trapped modes might need attention

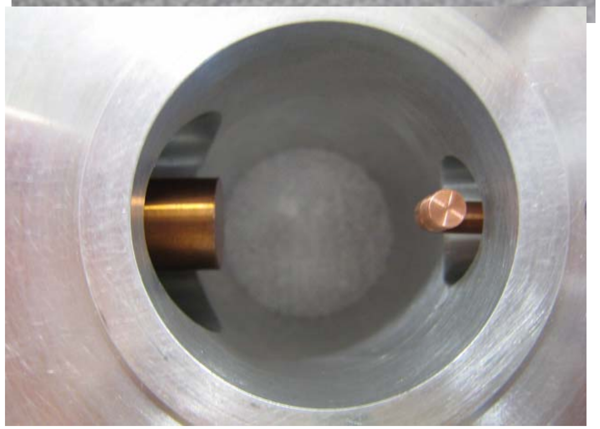
These specs are not tough but might need checking

LOM Coupler Prototype external Q measurements







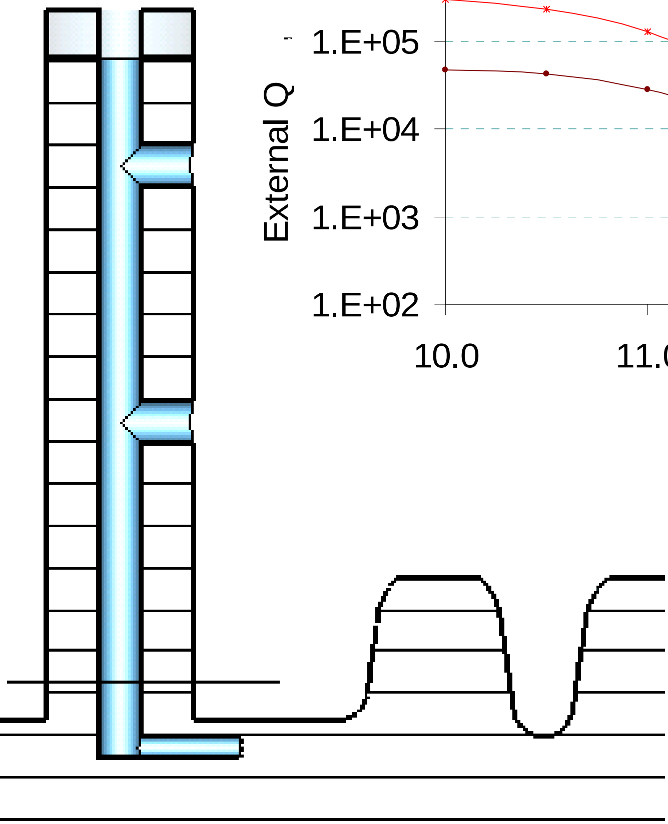


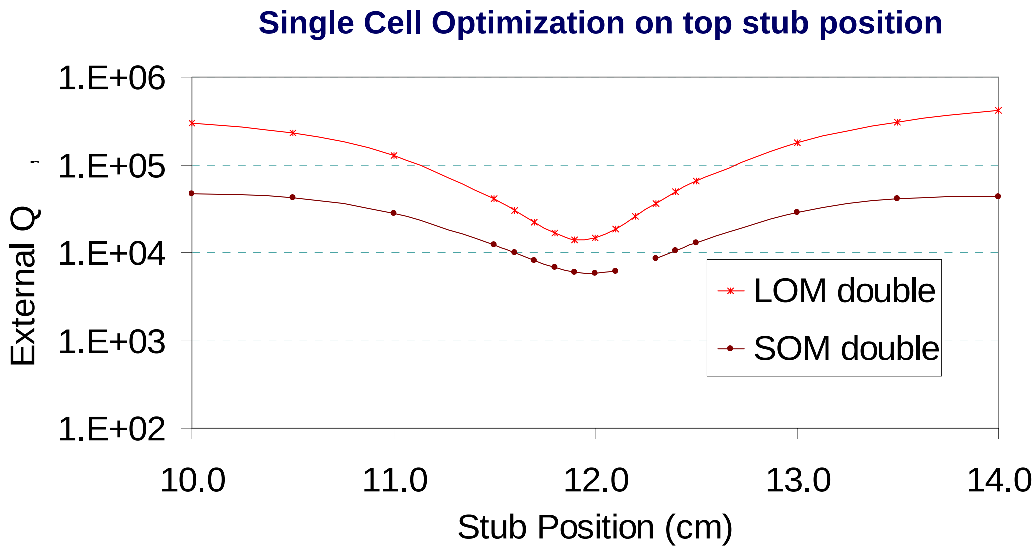
Method described in EuroTev Report 2007-036

New CI Integrated SOM and LOM coupler design

A double stub allows more flexible control of the coupler resonances.

Requires active damping of SOM to meet specs.





Initial optimisation for 9 cell cavity on a range of parameters including stub positions gave
Q external LOM = 4.0 E4
Q external SOM = 1.0 E5

Publications

Refereed Journals

G. Burt, R.M. Jones, A. Dexter, "Analysis of Damping Requirements for Dipole Wake-Fields in RF Crab Cavities." IEEE Trans. Nuc. Sci. Vol. 54, 2007

Refereed Conference

G. Burt, A. Dexter, L.Bellantoni, P. Goudket, C. Beard, A.Kalinin and L.Ma "Crab Cavity System for the ILC", 2005 ALCPG & ILC Workshops – Snowmass U.S.A. Status of the crab cavity system development for the ILC (Nanobeams 2005)

G. Burt, A. Dexter, L. Bellantoni, C. Beard, P. Goudket, "Progress Towards Crab Cavity Solutions for the ILC" EPAC 2006, Edinburgh, (MOPLS075).

G. Burt, A. Dexter, L. Bellantoni, C. Beard, P. Goudket, "Analysis of Wakefields in the ILC Crab Cavity", EPAC 2006, Edinburgh, 2006 (MOPCH163).

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