Crab cavity RF and testing for colliders

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ICFA beam dynamics workshops on deflecting/crabbing cavity applications in accelerators (2010)

Requirement and Status

ILC CRAB LLRF

- For ILC use 3.9 GHz s.c. cavities driven separately with solid state amplifiers (3 kW)
- Need accurate relative cavity phase control for 1 ms pulses
- Have demonstrated LLRF specification with RF interferometer
- Need amplitude control to counteract beamloading

CLIC CRAB LLRF

- For CLIC use 12 GHz n.c. travelling wave cavities driven with same Klystron (14 MW)
- Need to assess added phase noise on separate distribution paths
- RF test planned at CTF3 as part of EUCARD
- Need accurate relative cavity phase measurements for 200 ns pulses
- Need a laser interferometer (RF interferometer unlikely to be adequate)

LHC CRAB LLRF

- Anticipate a local crab crossing scheme < 0.522 mrad
- Anticipate 400 MHz CW compact s.c. cavities
- Meeting single pass synchronisation requirement is easy
- Meeting beam - beam instability synchronisation requirement is hard
- Preventing phase noise causing beam blow up is a worry

Crab Parameters

Beamloading with offset = a

$$P_b = \frac{a\ \theta_c\ q\ f_{rep}\ E_o}{2\ R_{12}}$$

	Max bunch offset (a)	crossing angle θ_c	bunch charge (q)	bunch repetition	Beam energy E_o	R12	Crab peak power
CLIC	0.4 mm	20 mrad	0.6 nC	2.00 GHz	1.5 TeV	25.0 m/rad	288 kW
LHC (local)	0.2 mm	0.52 mrad	18.4 nC	40.0 MHz	7.0 TeV	30.0 m/rad	12.7 kW
ILC	0.6 mm	14 mrad	3.2 nC	3.03 MHz	0.5 TeV	16.4 m/rad	1.24 kW

(Available forward power usually needs to be significantly higher than that extracted by the beam)
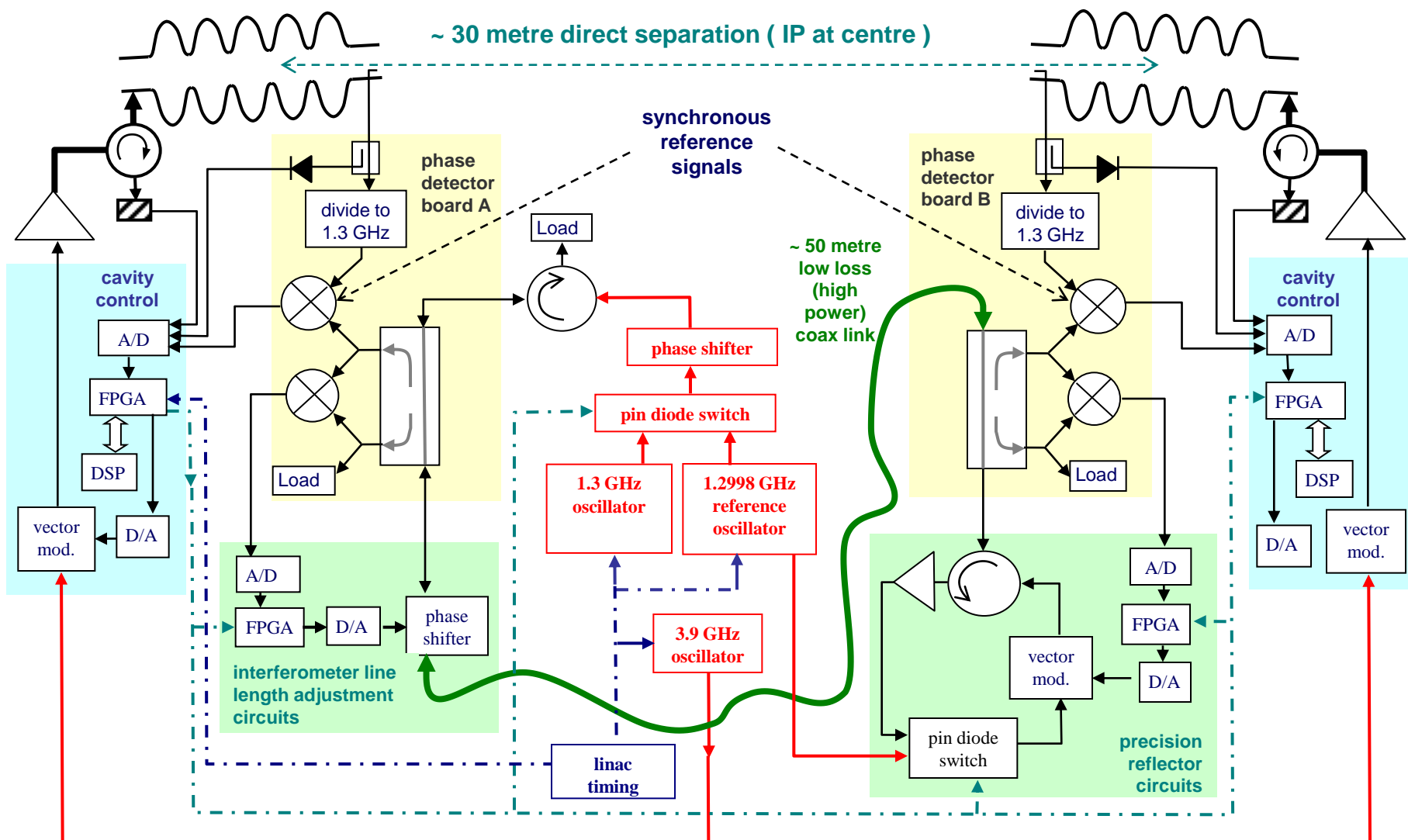
Cavity to Cavity Phase synchronisation requirement ϕ

$$= \frac{720\ \sigma_x f}{c\theta_c} \sqrt{\frac{1}{S_{rms}^4} - 1}\quad \text{degrees}$$

|	Luminosity fraction S	f (GHz)	σ_x (nm)	θ_c (mrads)	ϕ_{rms} (deg)	Δt (fs)	Pulse Length (μs)
CLIC	0.98	12.0	45	20	**0.0188**	4.4	0.14
LHC (single pass)	0.98	0.4	16500	0.52	**9.2**	63900	CW
LHC (multi- pass)	0.99999975	0.4	16500	0.52	**0.0305**	212	CW
ILC	0.98	3.9	655	14	**0.1271**	90.5	1000.00

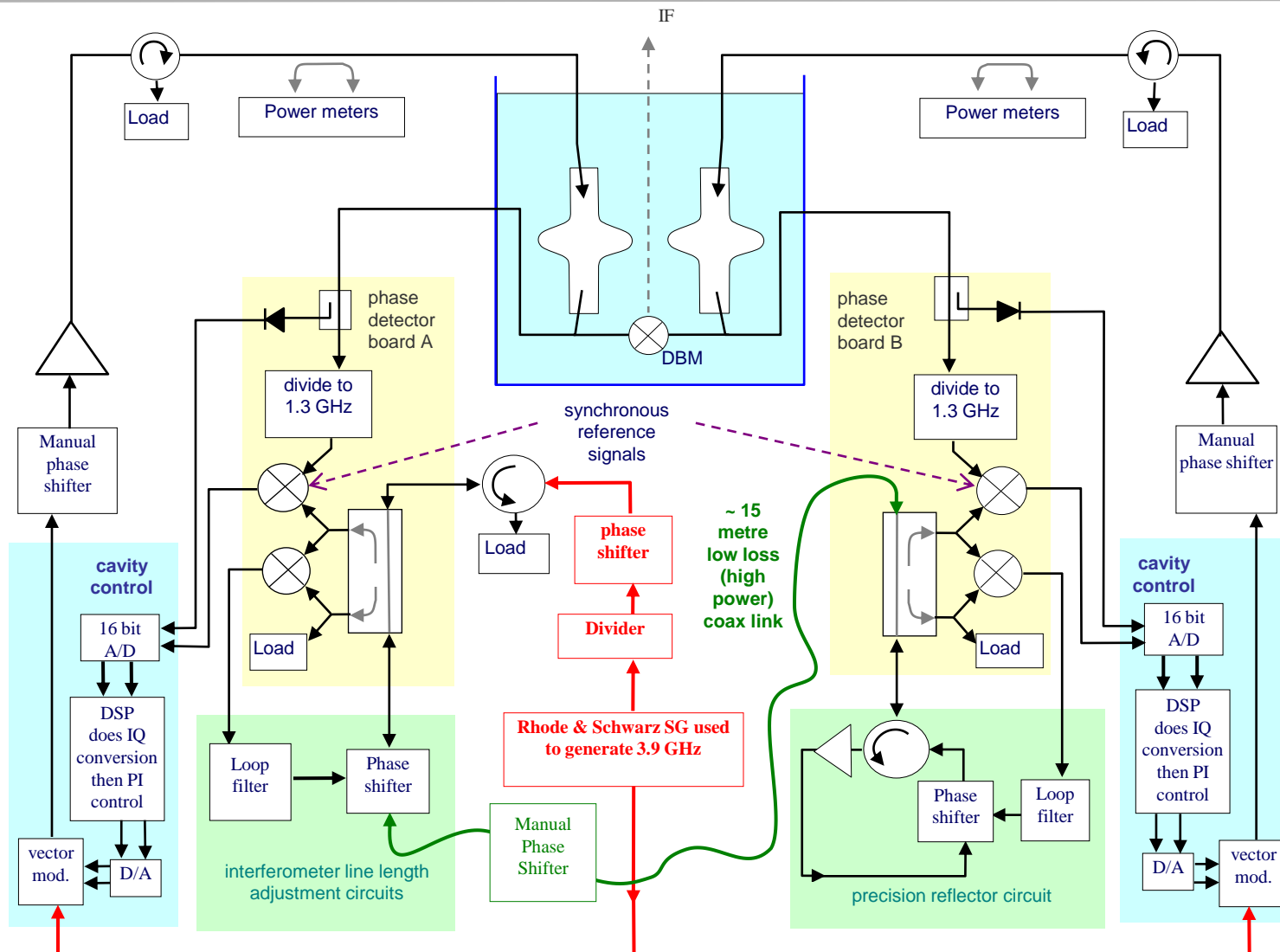# RF Interferometer for ILC Crab Synchronisation

ILC Crab VTF Proof of Principle

- Two single cell 3.9 GHz deflecting cavities were purchased from Niowave to perform cavity synchronisation tests.
- The cavities were both contained in a single cryostat and cooled to 4.2 K
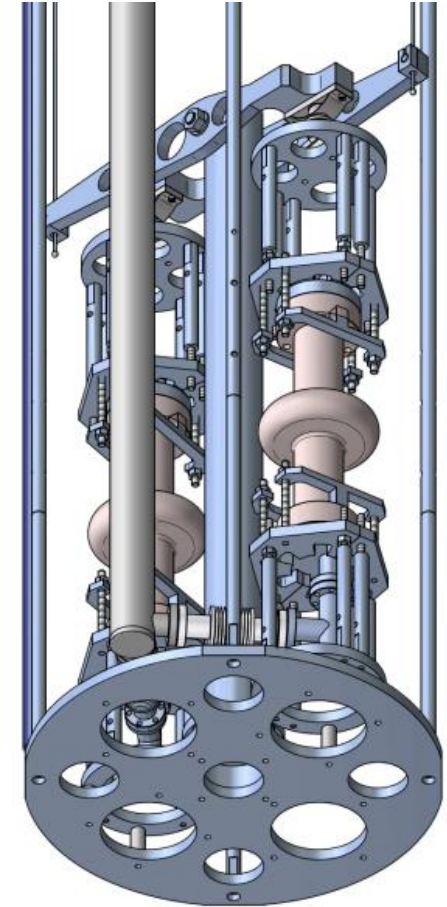
ILC Crab August 2008 test

- Double balanced mixer outside cryostat
- Achieved microphonic rejection to level of source noise
- Tuner resolution was poor making tuning difficult
- Tuner drift very large making simultaneous lock extremely difficult
- Simultaneous lock only achieve for a few tens of seconds
- Cavity to cavity jitter before lock = 4 deg and after lock = 100 milli-degrees r.m.s.

ILC Crab April 2009 tests
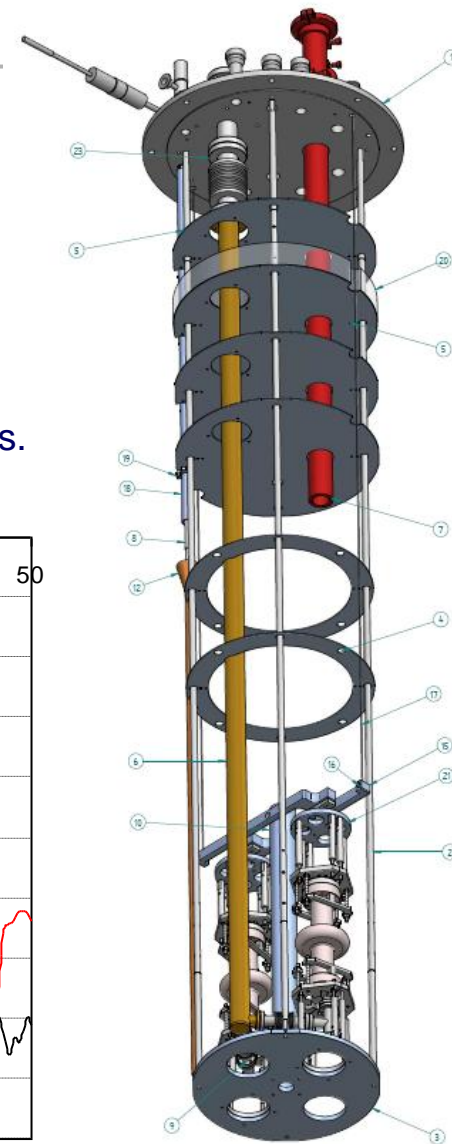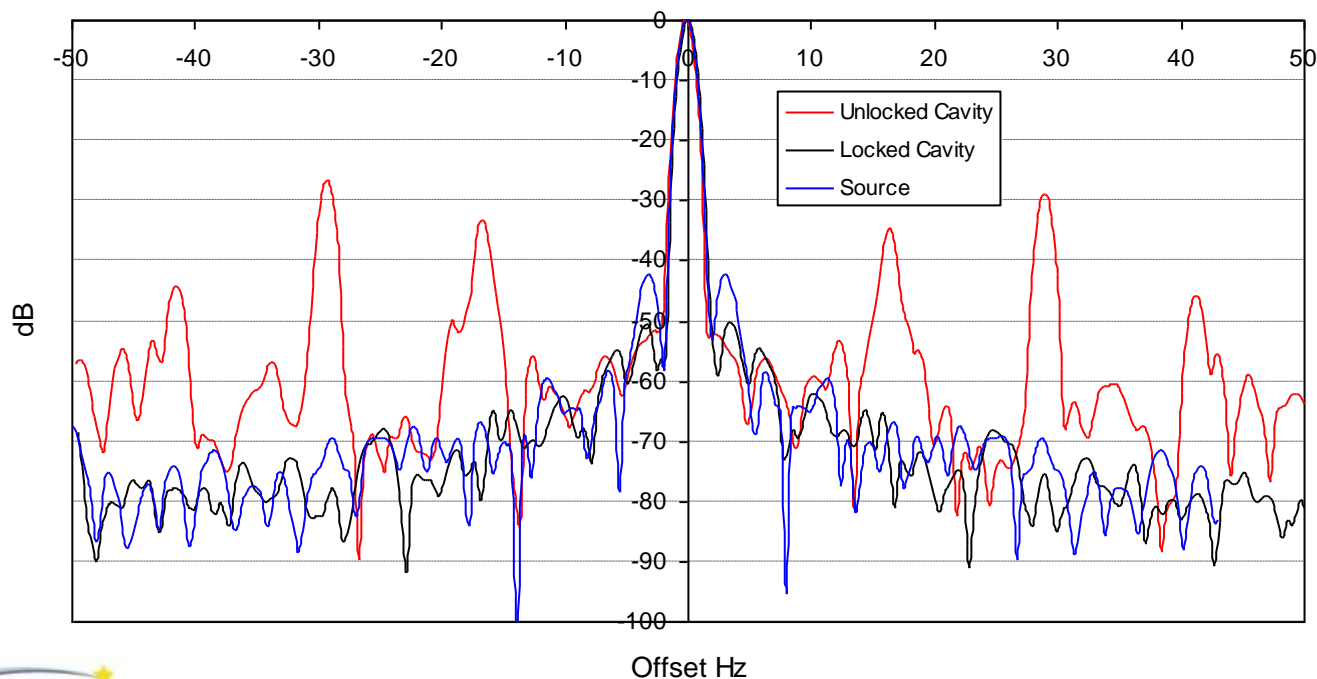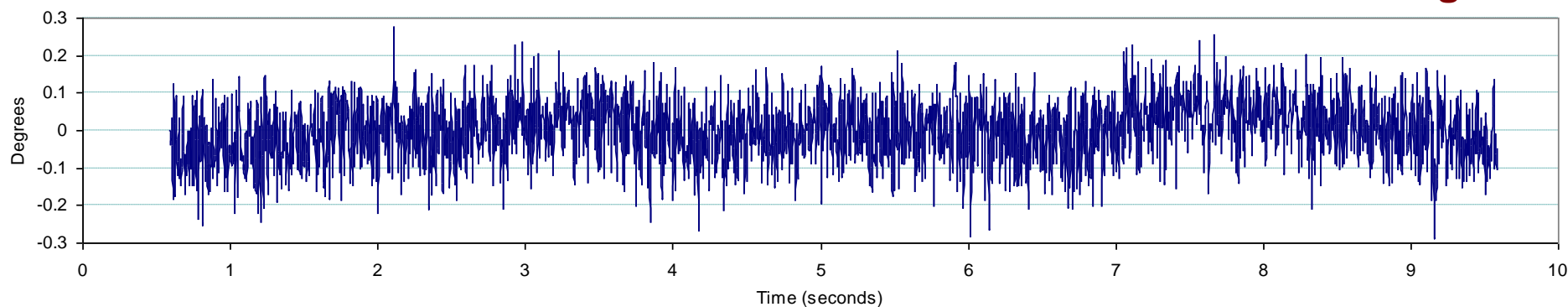
Measurements with Rhode & Schwarz source

Cavity to cavity phase jitter   **Control off   RMS ~ 0.8 degrees**
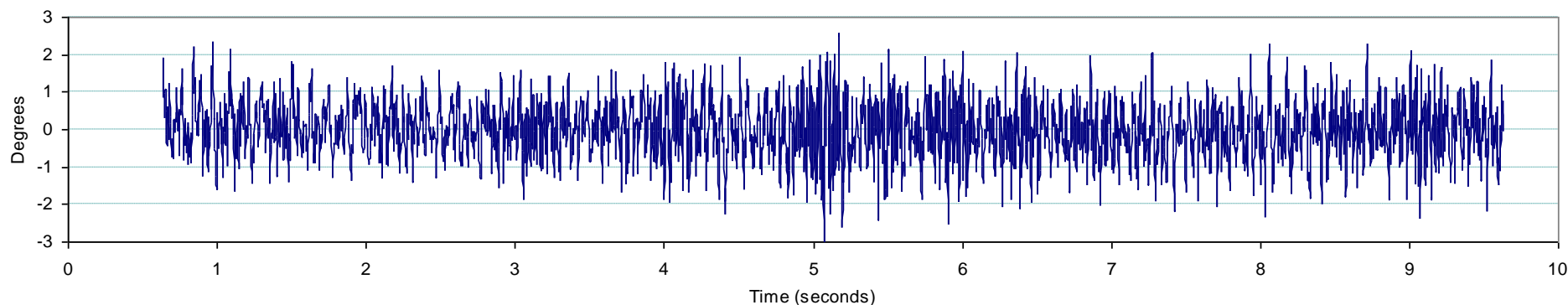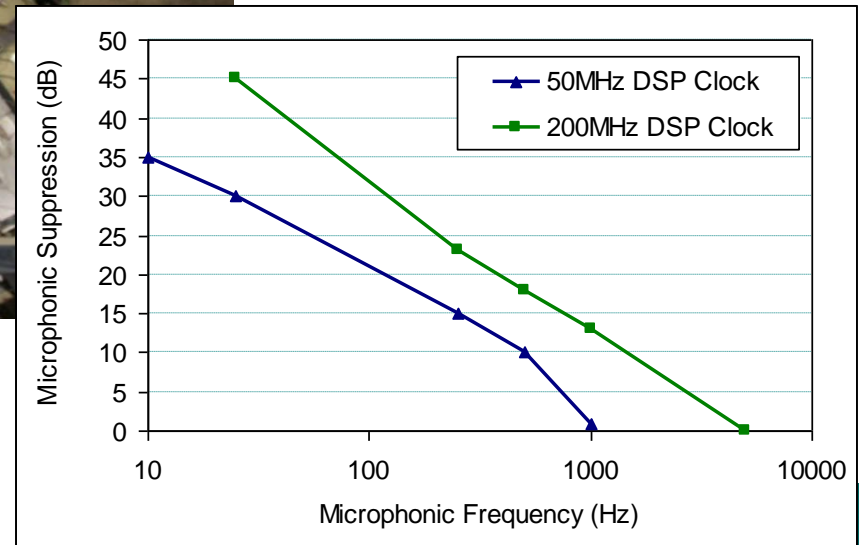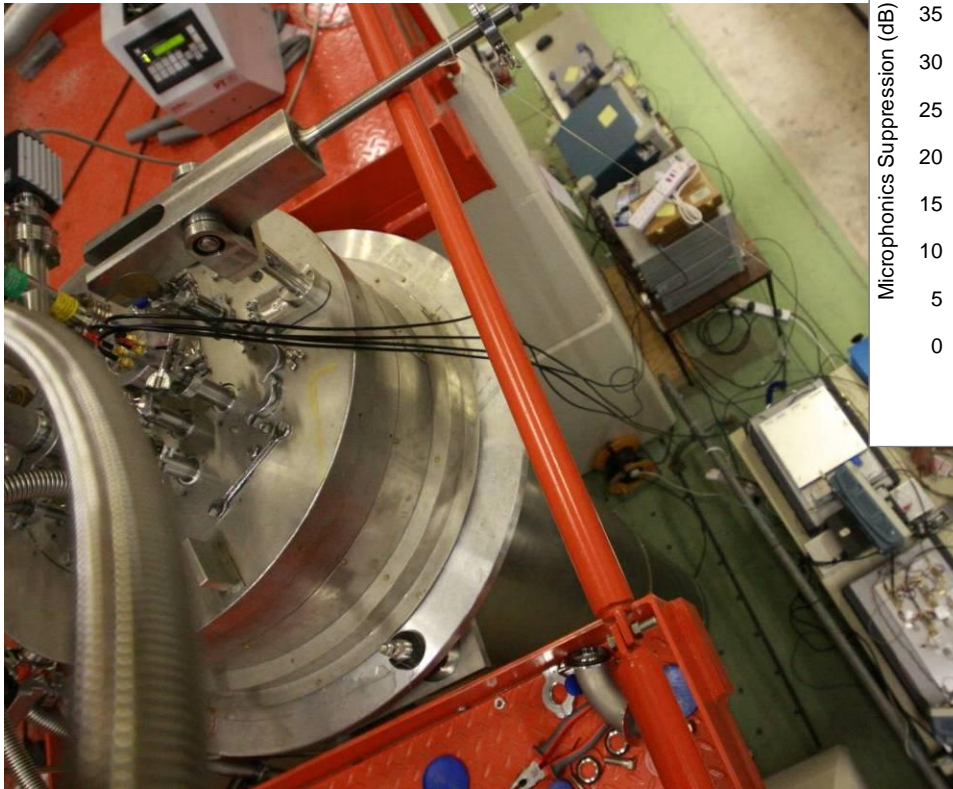

Cavity to cavity phase jitter   **Control on RMS ~ 0.08 degrees**
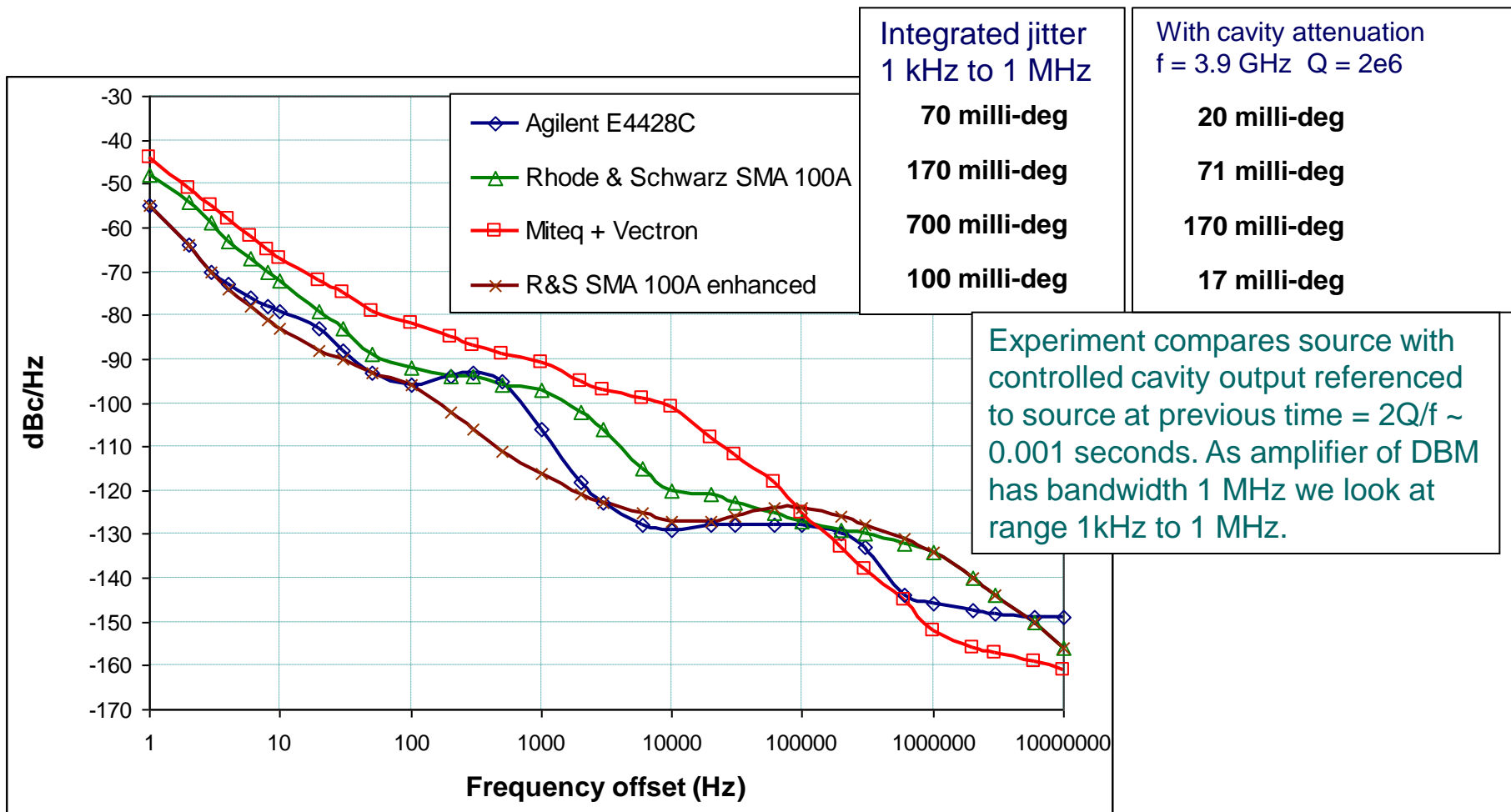
Microphonic suppression

ILC Crab April 2009 test
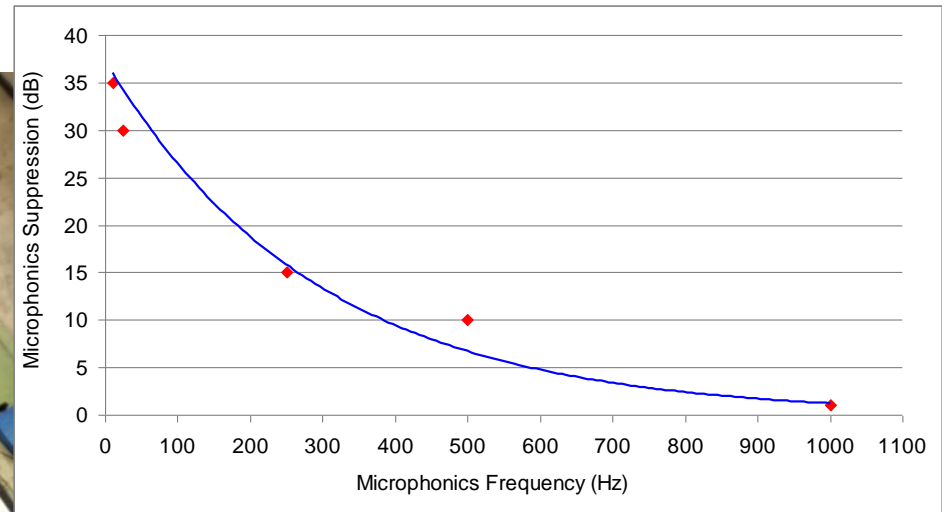
		Source	Period	Jitter (degrees)
1	Cavity to cavity control on	Vectron & Miteq	300 secs	0.1230
2	Cavity to cavity control on	Vectron & Miteq	10 secs	0.1080
3	Cavity to cavity control _off_	R&S SMA 100A	10 secs	0.7942
4	Cavity to cavity control on	R&S SMA 100A	10 secs	0.0852
5	Cavity to cavity control on	R&S SMA 100A	0.05 secs	0.0743
6	Cavity to cavity no interferometer	R&S SMA 100A	10 secs	0.0888
7	Cavity to cavity no interferometer	R&S SMA 100A	0.05 secs	0.0763
8	Cavity to source 1	R&S SMA 100A	0.05 secs	0.0576
9	Cavity to source 1	R&S SMA 100A	10 secs	0.0600

The tests started with our MITEQ DRO source stablised with our Vectron 10 MHz source. This was because the software on the Rhode an Schwarz SMA100A had been corrupted by X-ray exposure when left near to the Alice Booster. A replacement became available on the last day of testing.

Source comparison and performance limit

Integrated jitter 1 kHz to 1 MHz	With cavity attenuation f = 3.9 GHz Q = 2e6
70 milli-deg	**20 milli-deg**
170 milli-deg	**71 milli-deg**
700 milli-deg	**170 milli-deg**
100 milli-deg	**17 milli-deg**

Experiment compares source with controlled cavity output referenced to source at previous time = 2Q/f ~ 0.001 seconds. As amplifier of DBM has bandwidth 1 MHz we look at range 1kHz to 1 MHz.
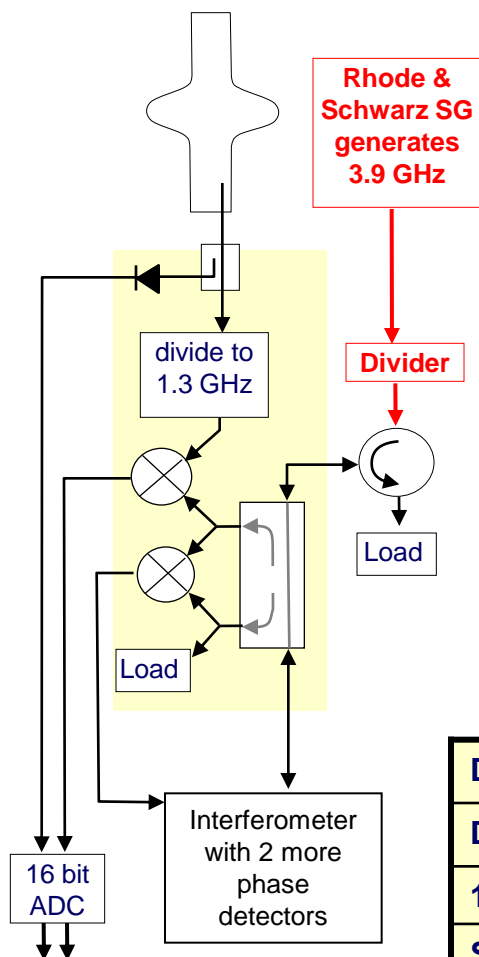
Note that comparing cavity output to source with DBM then if one signal to DBM is attenuated then the output at that frequency gets the same attenuation.

Cavity to Cavity

	Jitter at 1.3 GHz (milli-deg)	Contribution at 3.9 GHz (milli-deg)	No	Combine as	Running total
Cavity output divider	2	6	2	Un-correlated (rms)	9
Digital phase detectors	8	24	4	Un-correlated (rms with last)	49
13 ADC bits mapped to 100°		6	2	add ?	62
Source R&S >10 kHz		10	1	add ?	72
Source Miteq > 10 kHz		35		add to 62 above	97

Cavity to Source

Divider	2	6	1	rms	6
Dig. phase det.	8	24	2	rms	25
13 ADC bits to 100°		6	1	add ?	31
Source R&S >3 kHz		23	1	add ?	54

Phase synchronization 0.018 degrees

Amplitude stability better than 2%

Pulse length 120 ns

Real time control is probably impossible

- Design 12 GHz TW dipole copper cavity with high group velocity and thick irises

  ➢ 12 GHz is compact and has synergy with linac

  ➢ 12 GHz makes phase control tolerance larger than for sub harmonic frequency choices

  ➢ TW allows energy flow to mitigate beam-loading

  ➢ Thick irises reduces effects of pulse heating and phase drift

  ➢ Adjacent mode for SW cavities affect phase control performance

- Investigate various damping options

- Compute wakefields for designs with varied damping options

- If none of the damping schemes meet the specification then scale to lower frequency for smaller kicks

- Use single Klystron to drive both cavities

  ➢ Phase stability of Klystrons and the PET structures is very poor with respect to the cavity to cavity specification

To minimise required cavity kick R12 needs to be large (25 metres suggested)
Vertical kicks from unwanted cavity modes are bad one needs R34 to be small.
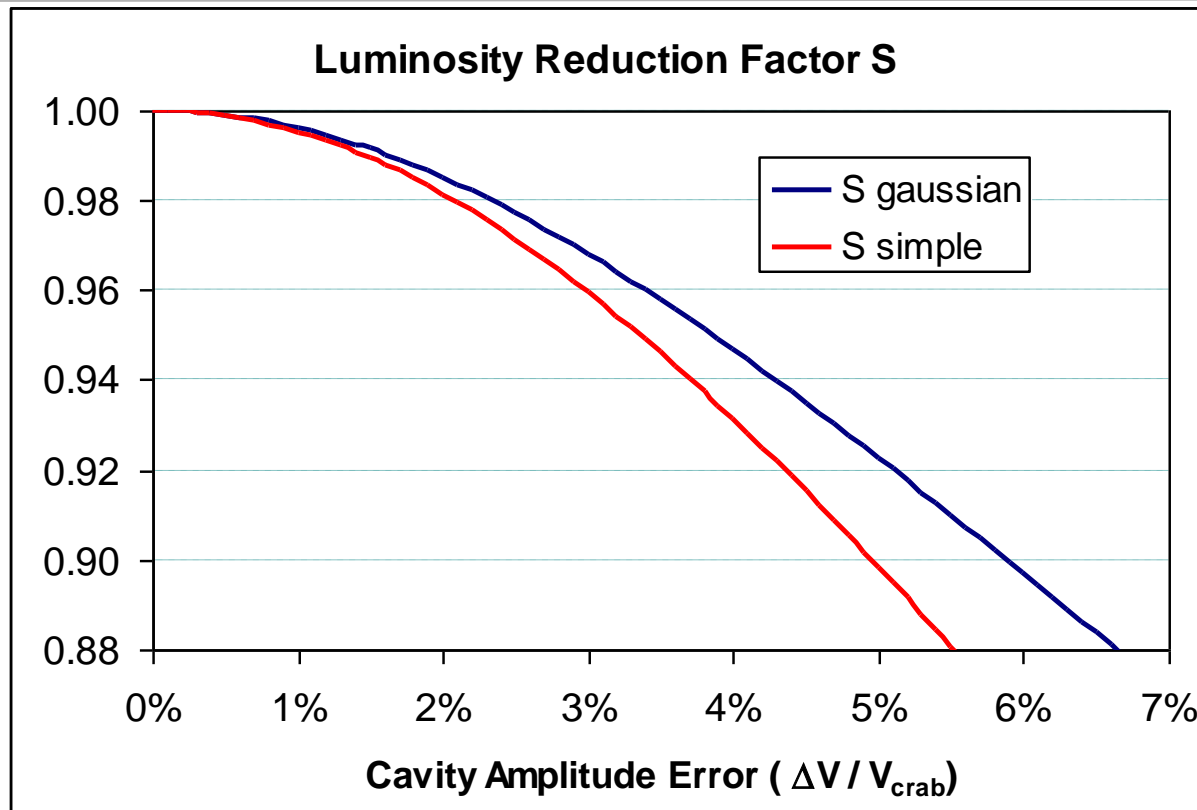For 20 mrad crossing and using as 12 GHz structure

$$V_{crab} = \frac{\theta_c E_o c}{2 R_{12} \omega} = \frac{2 \times 10^{-2} \times 1.5 \times 10^{12} \times 3 \times 10^{8}}{2 \times 25 \times 2\pi \times 12 \times 10^{12}} = 2.4 \text{ MV}$$

Error in kick tilts effective collision from head on.

Luminosity Reduction Factor
$$S \approx \frac{1}{\sqrt{1 + \left\{ \frac{\sigma_z \theta_c}{4\sigma_x} \frac{\left(\left|\delta V_1\right| + \left|\delta V_2\right| \right)}{V_{crab}} \right\}^2}}$$
gives

amplitude error on each cavity	1.0%	1.5%	2.0%	2.5%	3.0%
luminosity reduction	0.9953	0.9914	0.9814	0.9714	0.9596

Tolerance for Gaussian Amplitude Errors

Luminosity Reduction Factor S

σ_z = 44000 nm

σ_x = 45 nm

θ_c = 0.02 rad

$$\overline{S}\left(\frac{\Delta V}{V_{crab}}\right) = \frac{1}{2\pi\left(\frac{\Delta V}{V_{crab}}\right)^2} \int\limits_{-\infty}^{\infty} \frac{dV_1}{V_{crab}} \int\limits_{-\infty}^{\infty} \frac{dV_2}{V_{crab}} \frac{\exp\left\{-\frac{(V_1/V_{crab})^2}{2(\Delta V/V_{crab})^2}\right\} \exp\left\{-\frac{(V_2/V_{crab})^2}{2(\Delta V/V_{crab})^2}\right\}}{\sqrt{1 + \left\{\frac{\sigma_z \theta_c}{4\sigma_x} \frac{(|V_1| + |V_2|)}{V_{crab}}\right\}^2}}$$

CLIC LLRF Timing

21 km   2.75 km   0.05 km   2.75 km   21 km

Drive beams
12 GHz

Chicane
stretching

Chicane
stretching

PETS

PETS

Crab
cavity

Crab
cavity

IP

compressor   linac   linac   compressor

Klystron

LLRF   LLRF   LLRF   LLRF   LLRF

positrons   electrons

Bunch timing pick-ups   Bunch timing pick-ups

2 GHz bunch rep

Crab bunch timing pickups could be 2.75 km away from LLRF

Booster Linac
561 m
2.2 to 9.0 GeV

Synchronisation to main beam after booster linac. For a 21 km linac we have 140 μs between bunches leaving the booster and arriving at the crab cavities.

Crab Cavity RF

- **Beamloading constrains us to high power pulsed operation**
- **Intra bunch phase control looks impossible for a 140 ns bunch**

SOLUTION
- **One Klystron (~ 20 MW pulsed) with output phase and amplitude control**
- **Intra bunch delay line adjustment for phase control (i.e. between bunch trains)**
- **Very stable cavities**

CLIC LLRF Control Procedure
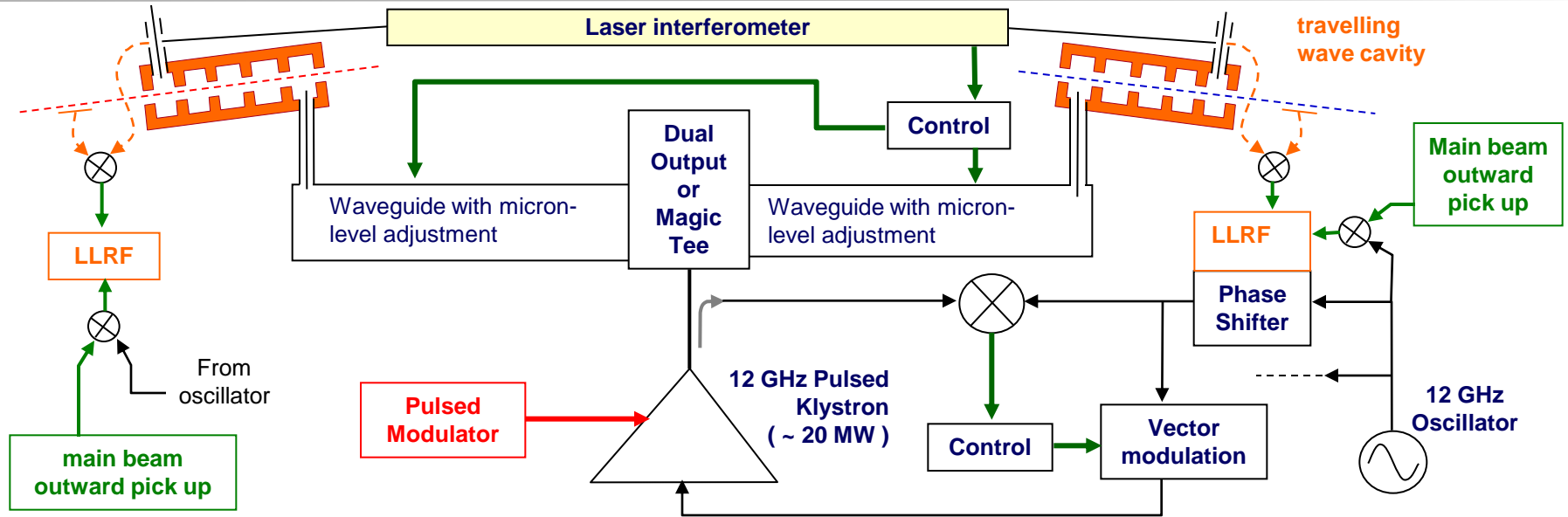
Once the main beam arrives at the crab cavity there is insufficient time to correct beam to cavity errors. These errors are recorded and used as a correction for the next pulse.

0. Send pre-pulse to cavities and use interferometer to measure difference in RF path length (option1)
1. Perform waveguide length adjustment at micron scale (option 2 use measurements from last pulse)
2. Measure phase difference between oscillator and outward going main beam
3. Adjust phase shifter in anticipation of round trip time and add offset for main beam departure time
4. Klystron output is controlled for constant amplitude and phase
5. Record phase difference between returning main beam and cavity
6. Alter correction table for next pulse

Beamloading in 16 Cell Cavity

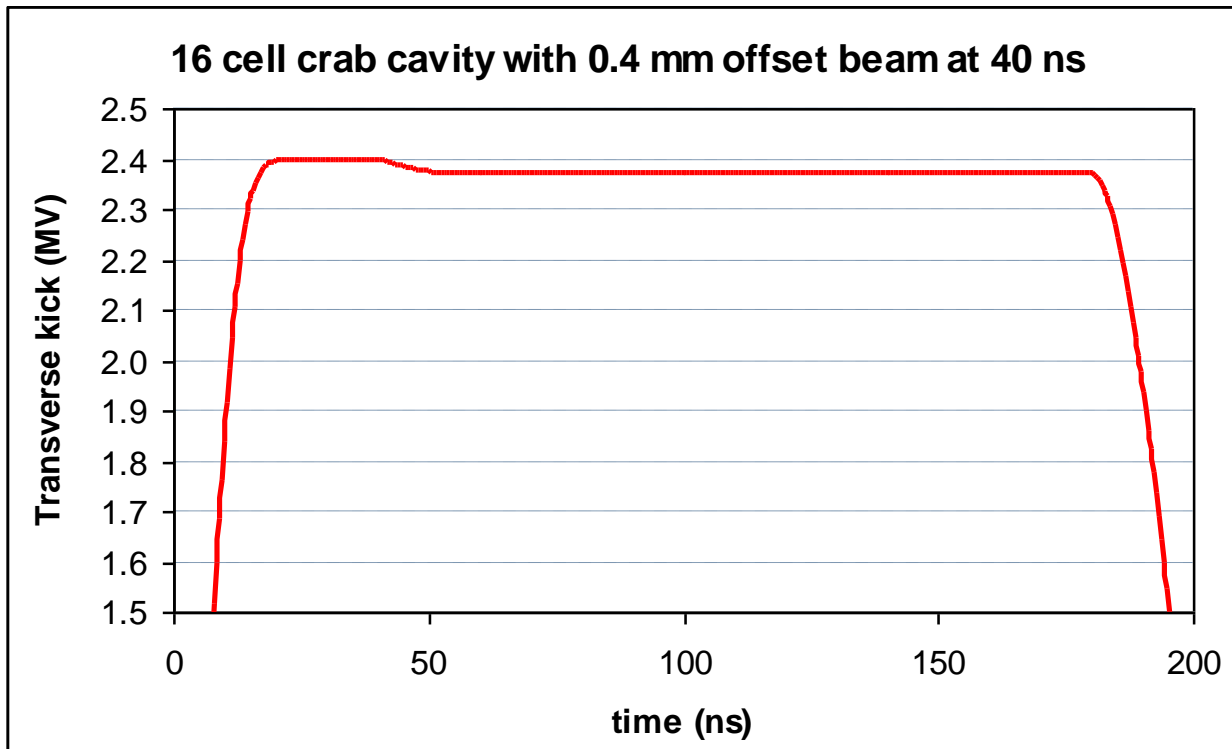Cavity Parameters as on last slide and Q = 6381

Beam offset (mm)	-0.4	0.0	0.4
Power entering cell 1 (MW)	6.388	6.388	6.388
Power leaving cell 16 (MW)	5.619	5.341	5.063
Ohmic power loss (MW)	1.071	1.047	1.023
Beamload power loss (MW)	-0.302	0.000	0.302
E max for cell 1 (MV/m)	51.1	51.1	51.1
Efficiency	12.04%	16.39%	20.74%
Kick (MV)	2.428	2.400	2.372

A short inefficient cavity with a high power flow achieves adequate amplitude stability

Can we make the gradient?

Is pulse heating OK (consider low temperature operation)?

ICFA beam dynamics workshops on deflecting/crabbing cavity applications in accelerators (2010)

Fill Time and Beamloading

16 cell crab cavity with 0.4 mm offset beam at 40 ns

Input = 6.45 MW
**Initial kick = 2.40 MV**
Plateau = 2.37 MV

v_g = group velocity
L_{cell} = cell length
U_n = energy in cell n
f_{rep} = bunch frequency
q = bunch charge
δx = bunch offset

For each cell solve energy equation

$$\frac{dU_n}{dt} = \frac{(U_{n-1} - U_n)}{L_{cell}} v_g \quad - \quad U_n \frac{\omega}{Q} \quad - \quad q\, f_{rep}\, \delta x\, \omega \sqrt{\frac{\omega}{c}\frac{R}{Q}U_n} \qquad (n > 1)$$

convection - dissipation - beamloading

We are constructing a 11.424 GHz
7 cell travelling wave crab cavity in
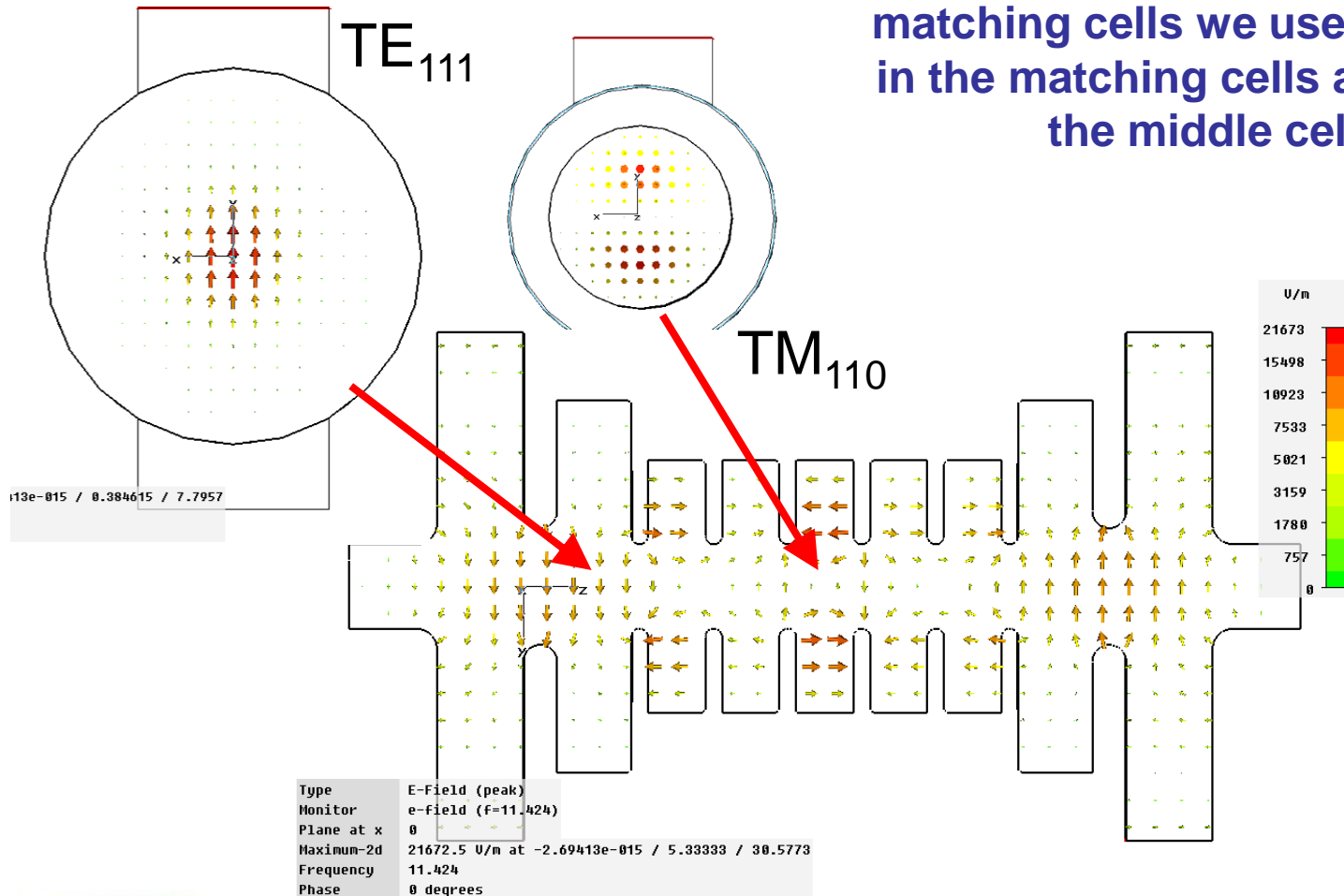order to perform high gradient tests
of the structure.

V/m	
21670	
20315	
17607	
14898	
12189	
9481	
6772	
4063	
1354	
0	
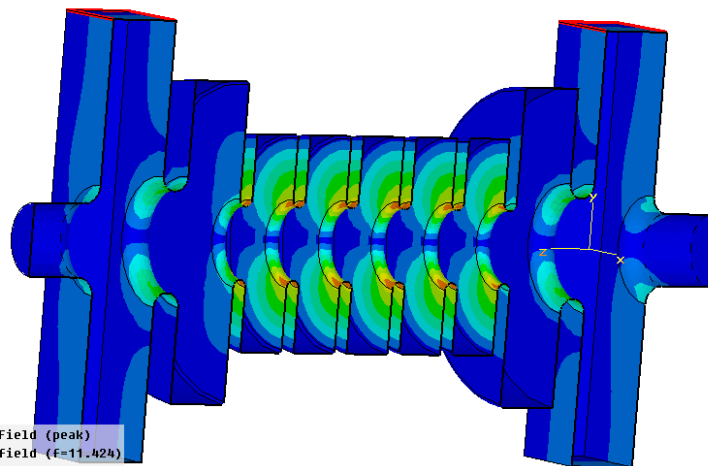
Type   E-Field (peak)
Monitor   e-field (f=11.424)
Component   Abs
Maximum-3d 23844.9 V/m at 0.769231 / 5.66667 / 32.244
Frequency   11.424
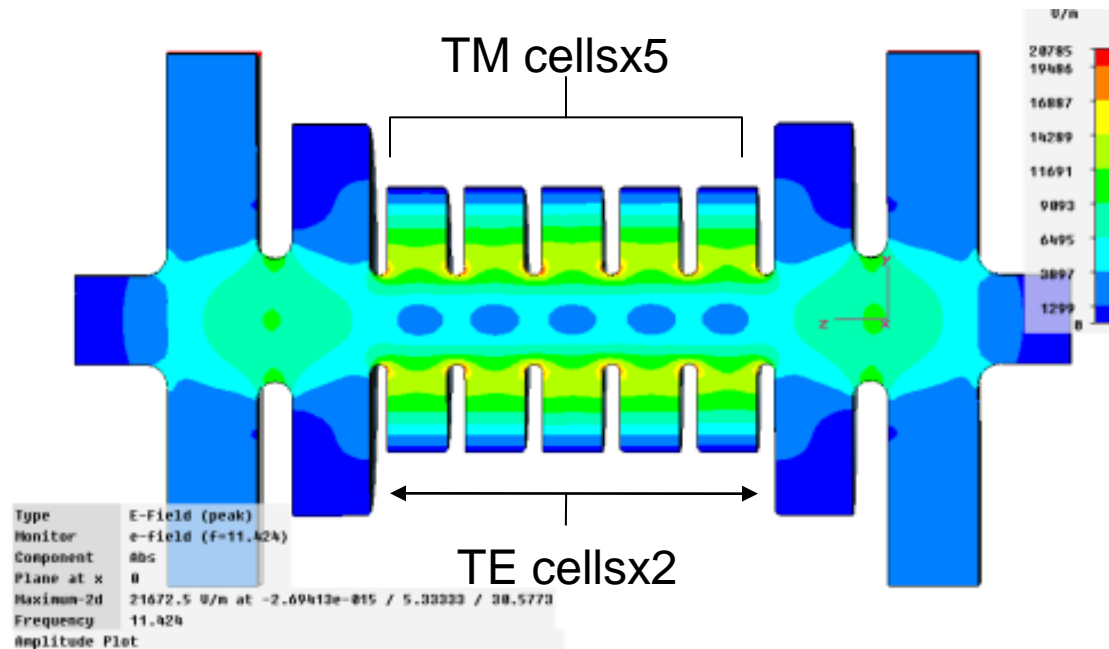Amplitude Plot
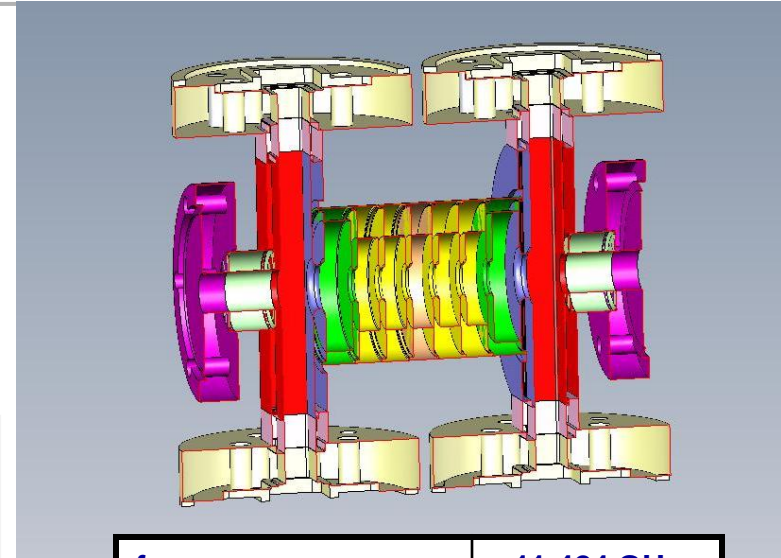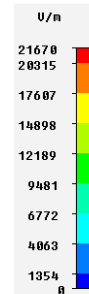
frequency	11.424 GHz
phase adv. per cell	120°
mid cell mode	~ TM110
mid cell lengths	8.747 mm
iris radius	
iris thickness	2.390 mm
mid cell dia.	28.986 mm
end cell mode	~ TE111
end cell dia.	44.000 mm

Structure Design

In order to have low fields in the matching cells we use the TE_{111} mode in the matching cells and the TM_{110} in the middle cells only.

TE_{111}

TM_{110}

13e-015 / 0.384615 / 7.7957

	U/m
	21673
	15498
	10923
	7533
	5021
	3159
	1780
	757
	0

| Type	E-Field (peak)
Monitor	e-field (f=11.424)
Plane at x	0
Maximum-2d	21672.5 U/m at -2.69413e-015 / 5.33333 / 30.5773
Frequency	11.424
Phase	0 degrees

High power test cavity (11.424 GHz)

- To determine the maximum operating gradient for the crab cavity

- Needs special design of the test cavity, compatible with the SLAC high power klystron and test stand

- The mid cells operate at TM_{110} dipole mode for maximum axial field while the matching end cells at TE_{111} dipole mode so that axial field =0


TM cellsx5

TE cellsx2

	U/m
	20785
	19486
	16887
	14289
	11691
	9093
	6495
	3897
	1299
	0

Type   E-Field (peak)
Monitor   e-field (f=11.424)
Component Abs
Plane at x 0
Maximum-2d 21672.5 U/m at -2.69413e-015 / 5.33333 / 30.5773
Frequency 11.424
Amplitude Plot

peak electric field = 90 MV/m

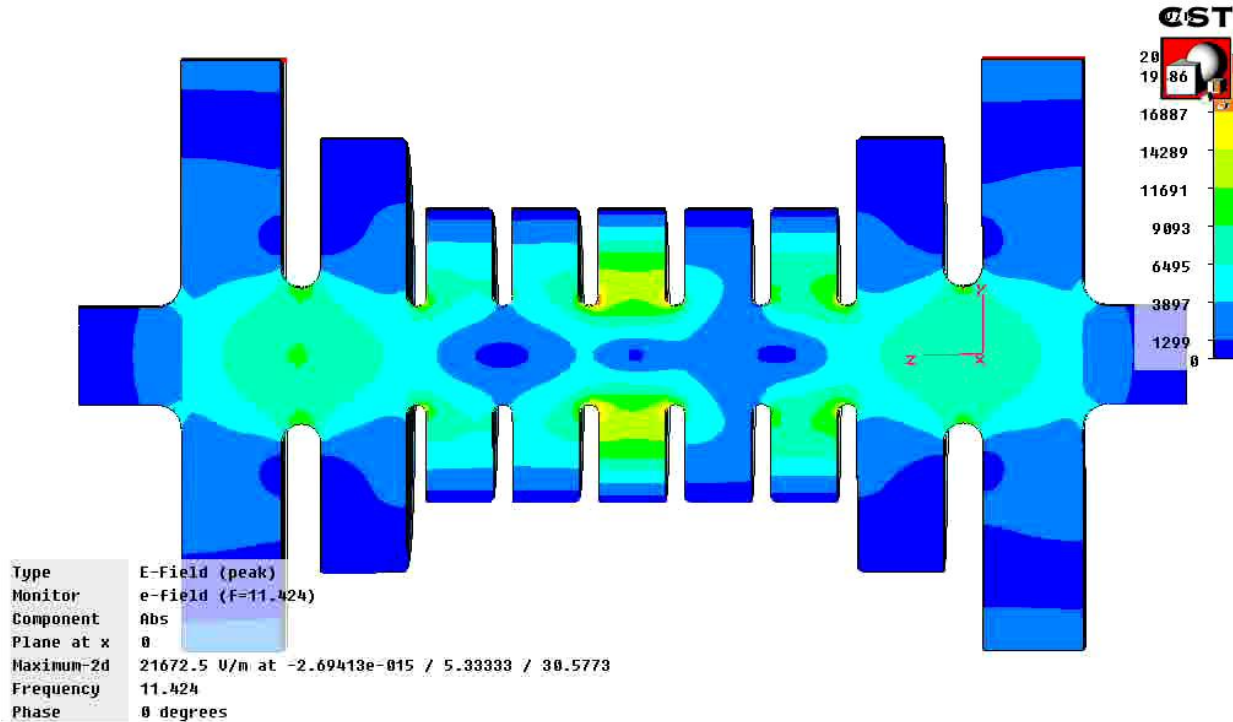peak magnetic field = 350 kA/m

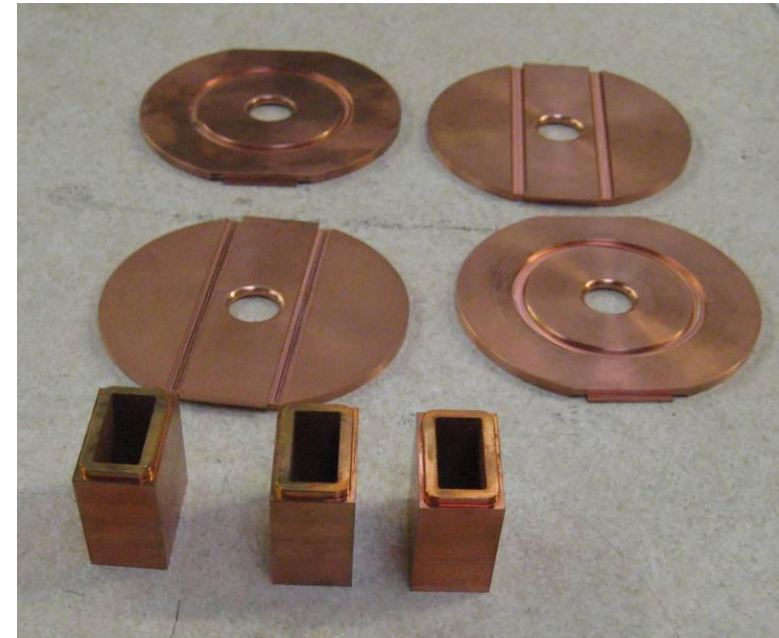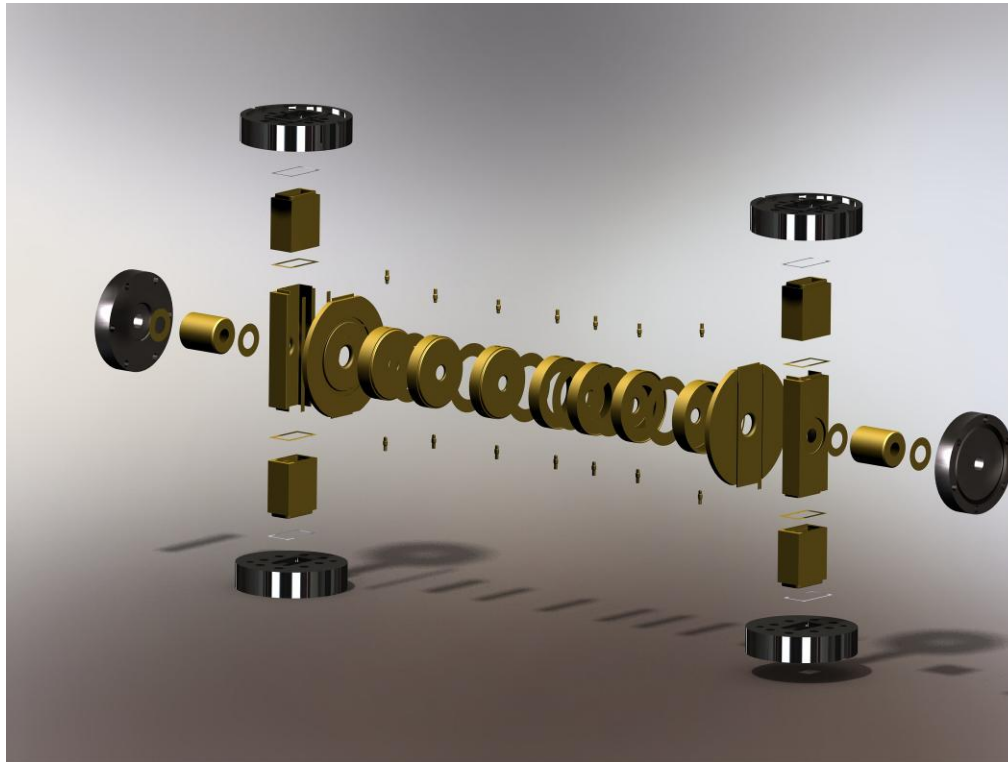transverse gradient = 37 MV/m

input power = 20 MW
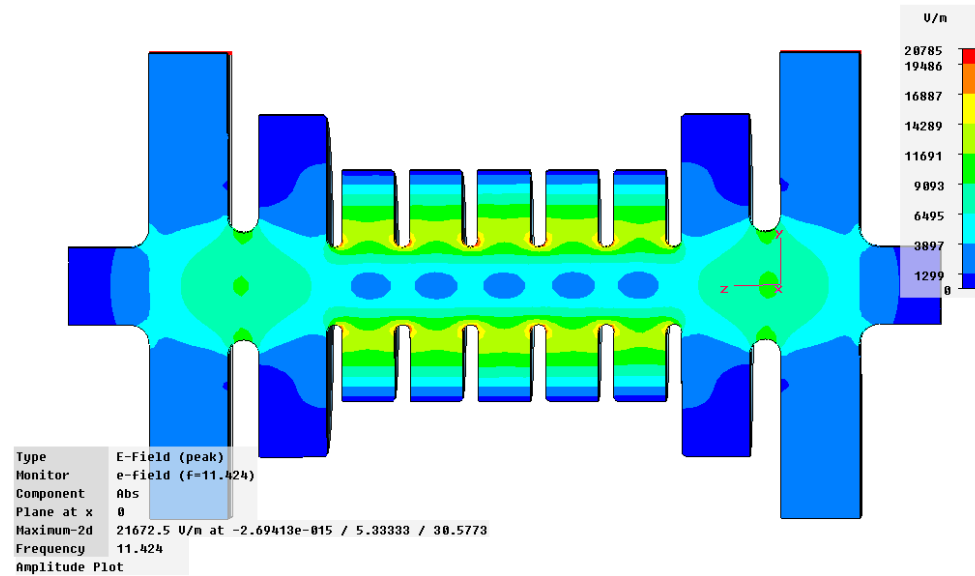
The five mid cells show a good field flatness and the reflections are low at the operating frequency.
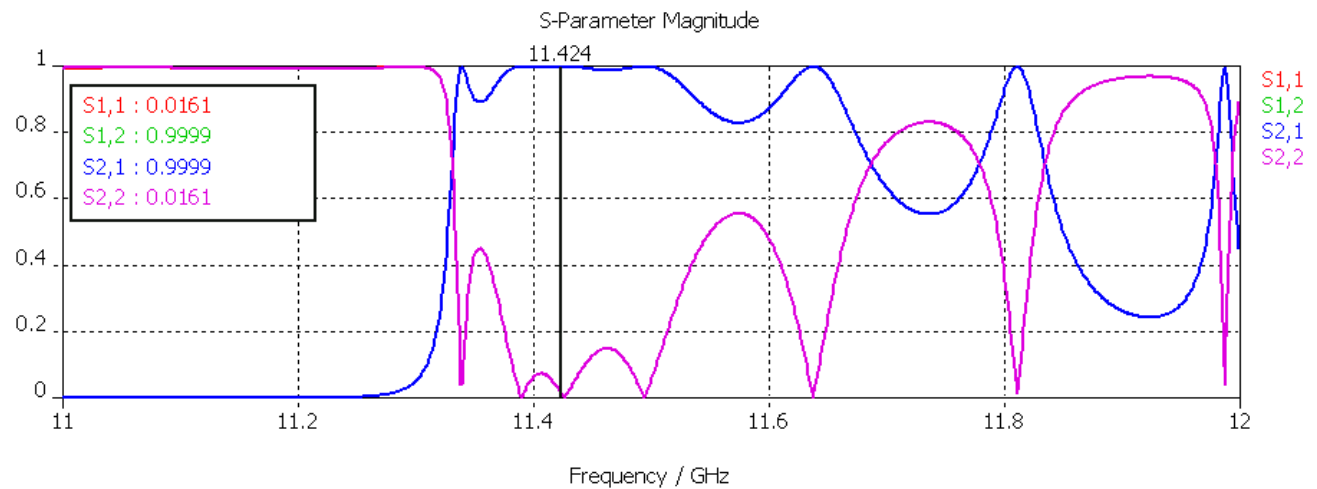
The structure has a peak electric field of 90 MV/m and a peak magnetic field of 350 kA/m for 20 MW input power.

Machining is in the final stage at Shakespeare Engineering, Chelmsford

- Anticipate a local crab crossing scheme < 0.522 mrad

- Anticipate 400 MHz SCRF cavities

- Anticipate no installation on LHC before 2019

- Meeting single pass synchronisation requirement is easy

- Meeting beam – beam offset instability synchronisation requirement is much more difficult.

- Preventing phase noise causing beam blow up a worry

Ohmi K. et al. "Beam-beam effect with an external noise in LHC", TUPAN048 PAC07

CONCLUSION

Emittance growth and luminosity decrement due to external noise in beam-beam collision system have been studied. To achieve 1 day luminosity life time, the noise $(\delta x/\sigma_x)$ should be 0.1% for turn by turn noise ($t_{cor} = 1$ turn). If the correlation time of the noise is 100 turn, the tolerance is 1%. The tolerance roughly scale the correlation time as $\sqrt{t_{cor}}$. The noise level 0.1% correspond to phase fluctuation 0.6 mrad using $\Psi_{RF} = 10^{-3}\omega_{RF}\sigma_x/c\tan\phi$, where $\omega_{RF} = 2\pi \times 400$ MHz, $\phi = 0.22$ mrad.

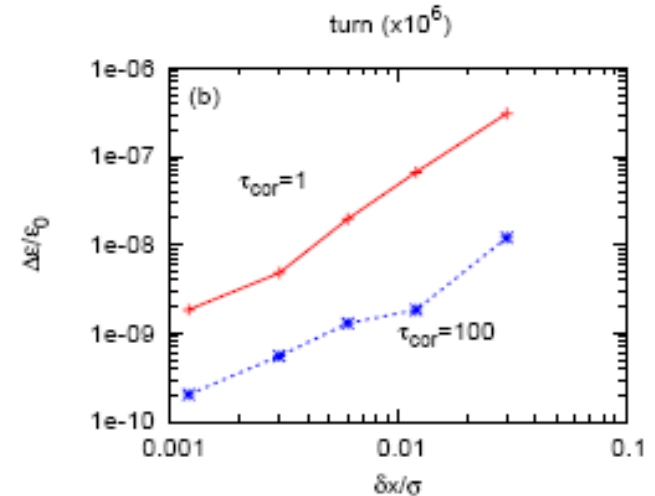**ϕ is the half crossing angle**

Figure 2: Emittance growth due to the fluctuation given by the strong-strong simulation. t_{cor} is the correlation time (turn) of the fluctuation.

If at IP bunches have horizontal displacement 0.5Δx and Gaussian profile then the integral determining the geometric luminosity contains the term

$$f(x) = \frac{1}{2\pi\sigma_x^2} \exp\left[-\frac{(x+0.5\,\Delta x)^2}{2\sigma_x^2}\right] \exp\left[-\frac{(x-0.5\,\Delta x)^2}{2\sigma_x^2}\right]$$

Luminosity reduction is therefore
$$S = \exp\left(-\frac{\Delta x^2}{4\sigma_x^2}\right) \approx S_{rms} = \left(1+\frac{\Delta x^2}{\sigma_x^2}\right)^{-0.25}$$

If $\quad \dfrac{\Delta x}{\sigma_x} = 0.001 \quad$ **then** $\quad S = 0.99999975$

For phase error ϕ we have
$$\frac{\Delta x_{ip}}{\sigma_x} = \frac{c\,\theta_c}{2\sigma_x}\frac{\sin(\phi)}{\omega} \approx \frac{c\,\theta_c\,\phi}{2\sigma_x\,\omega}$$

Hence $\quad \phi = \dfrac{4\pi\sigma_x f}{c\theta_c}\dfrac{\Delta x_{ip}}{\sigma_x} = \dfrac{4\pi\times 16.5\times 10^{-6}\times 4\times 10^{8}}{3\times 10^{8}\times 0.00052}\times 0.001 = 5.32\times 10^{-4} \quad$ rad

Transverse bunch by bunch feedback should eliminate the requirement for an interferometer between crab cavities

LHC beams are extremely stable get accurately driven into collision by other control loops, stability is therefore the key requirement rather than synchronisation.

Phase noise at "dangerous frequencies" will expand bunches and reduce lifetime.

Radiation damping maintains bunch size for small levels of phase noise at KEK-B, this will not apply to LHC.

The KEK_B experiment for coherent noise, for a well designed system noise at dangerous frequencies will be incoherent.

Calaga et al. "Status of LHC Crab Cavity simulations and beam studies", CERN-ATS 2009-035
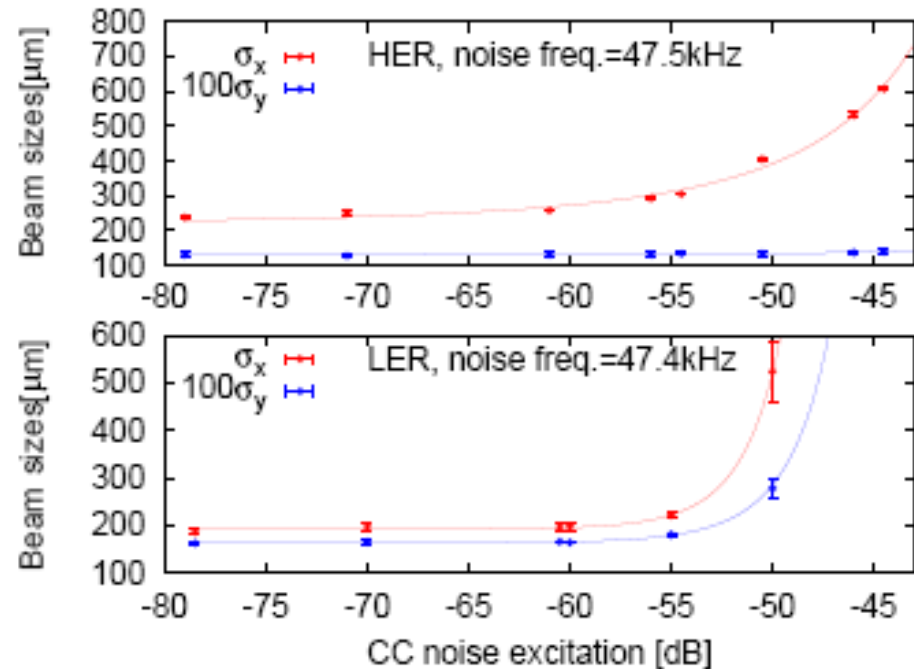

Figure 1: Beam size versus RF phase noise when exciting the LER and HER CCs individually.

Following the successful commissioning of the KEK-B crab cavity [3], experiments targeted to assess the impact of the RF phase noise and other measurements relevant to crab cavity beam dynamics were performed. The noise studies consisted of scanning the RF phase noise in the CCs and measure the corresponding beam size blow-up. Figure 1

Crab Phase Noise and Beam Blow-Up

At operating freq. kick is synchronised to revolution hence is identical on each pass. For non integer betatron wavelengths on loop, the return point cycles.
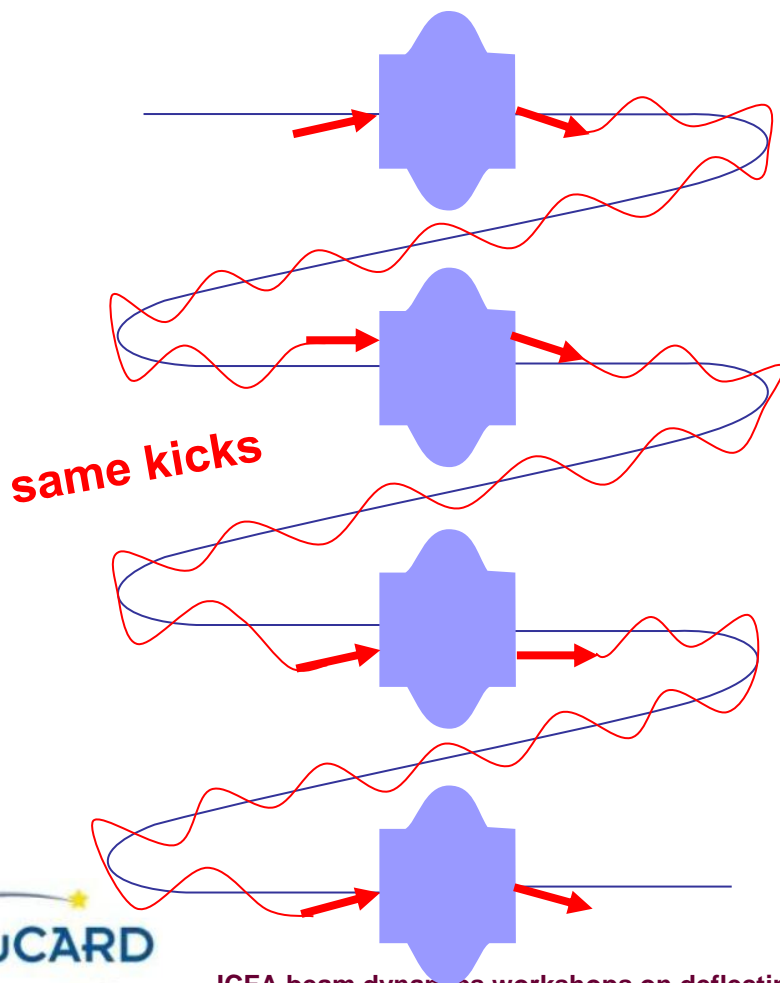
Blow up when kick from (coherent) noise at an offset frequency synchronises to the betatron offset frequency. (i.e. kick always reinforces oscillation)

same kicks

different kicks but reinforcing

Collimator
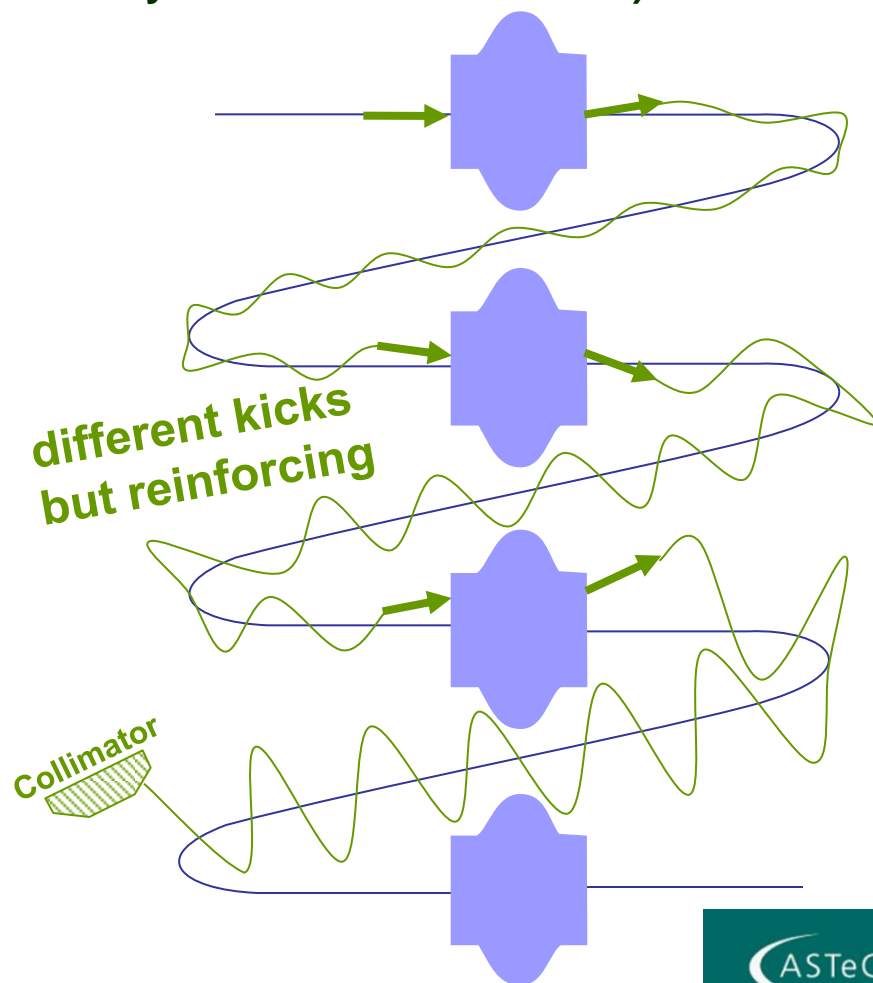
Kotzian G, Holfe W. and Vogel E. "LHC Transverse Feedback Damping Efficiency", THPP114 EPAC08
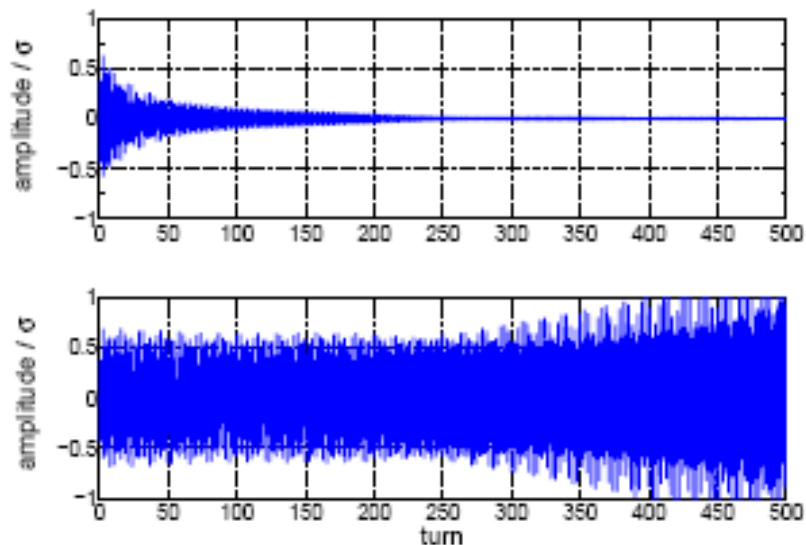

Figure 4: Turn-by-turn bunch oscillation amplitudes with feedback on (top) and off (bottom).

Transverse damping will remove oscillations of the entire bunch in two hundred turns and so it is the magnitude of differential kicks that matters with respect to an order of magnitude estimate of RF crab cavity noise limits at the synchrotron frequency minus the betatron frequency.

Non Coherent Phase Noise

For incoherent phase noise, kicks add for a time period, then add for another time period in a different phase space direction. Motion towards the collimator is a random walk hence distance travelled goes as revolutions squared. e.g. if coherent noise causes some particles to hit the collimator after 11,200 turns then with incoherent noise lifetime is estimated as 125×10^6 turns.

- **Only consider differential kicks, these are maximum at the crabbing phase**

- **Assume design kick (single pass) puts particles at end of bunches on paths that just miss the collimators (without anti-crab).**

- **To make 11,200 revolutions with a coherent noise source, reduce cavity field with respect to operating field by 40.5 dB hence power by 80.8dB. (assume no anti-crabbing effect)**

- **Hence to make 121×10^6 revolutions with incoherent noise source reducing power by 81 dB is sufficient**

- **For LHC then 121×10^6 revolutions ~ 3 hours so need an extra factor of ten, i.e. 110,000 revolutions hence 101 dB is needed.**

- **As the noise will not always be at the perfect crabbing phase and there may be other damping effects -101 dB is a worst estimate requirement.**

1. Careful selection of master oscillator

2. Limit bandwidth of SCRF cavities with respect to the offset frequency of the first dangerous frequency = 11 kHz (revolution) – 3 kHz (Betatron)

3. Balance ultimate phase control of cavities using a large gain in the LLRF control system against increase noise outside loop bandwidth

4. Consider analogue control rather than digital control where sampling and clock jitter could add noise

5. Use IOT amplifiers (in linear regime) rather than Klystrons

6. Use local crossing scheme and promote cancellation of phase noise effects originating from the oscillator between crab and anti-crab cavities

Winter, Schmüser, Ludwig, Schlarb, Chen, Kartner and Ilday, "High Precision Laser Maser Oscillators…", (EPAC 2006) THPPA01

Must lock oscillator so that the shoulder of the phase noise is before dangerous frequencies.

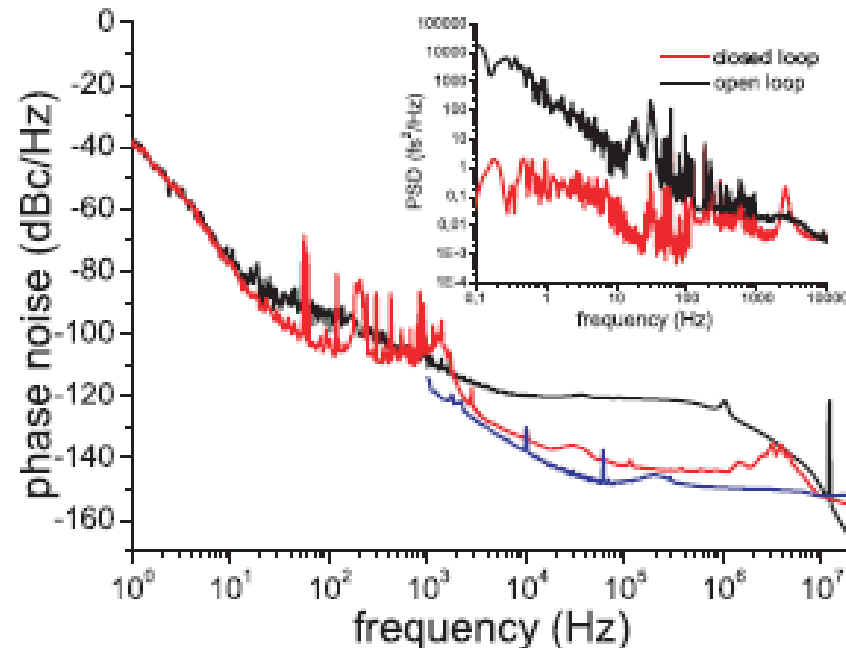Phase noise in dangerous range of 7 kHz to 100 kHz can be < -125 dBc/Hz


Figure 6: Single sideband phase noise of the Bates Master Oscillator (MO) (black), the EDFL locked to the reference after transmission through the link (red) and the free running EDFL (blue). Inset: Mixer output signal of the RF fiber link stabilization.

The e2v IOTD2130 installed at Diamond can be tuned to 400 MHz and will deliver 80 kW c.w. and 140 kW pulsed.
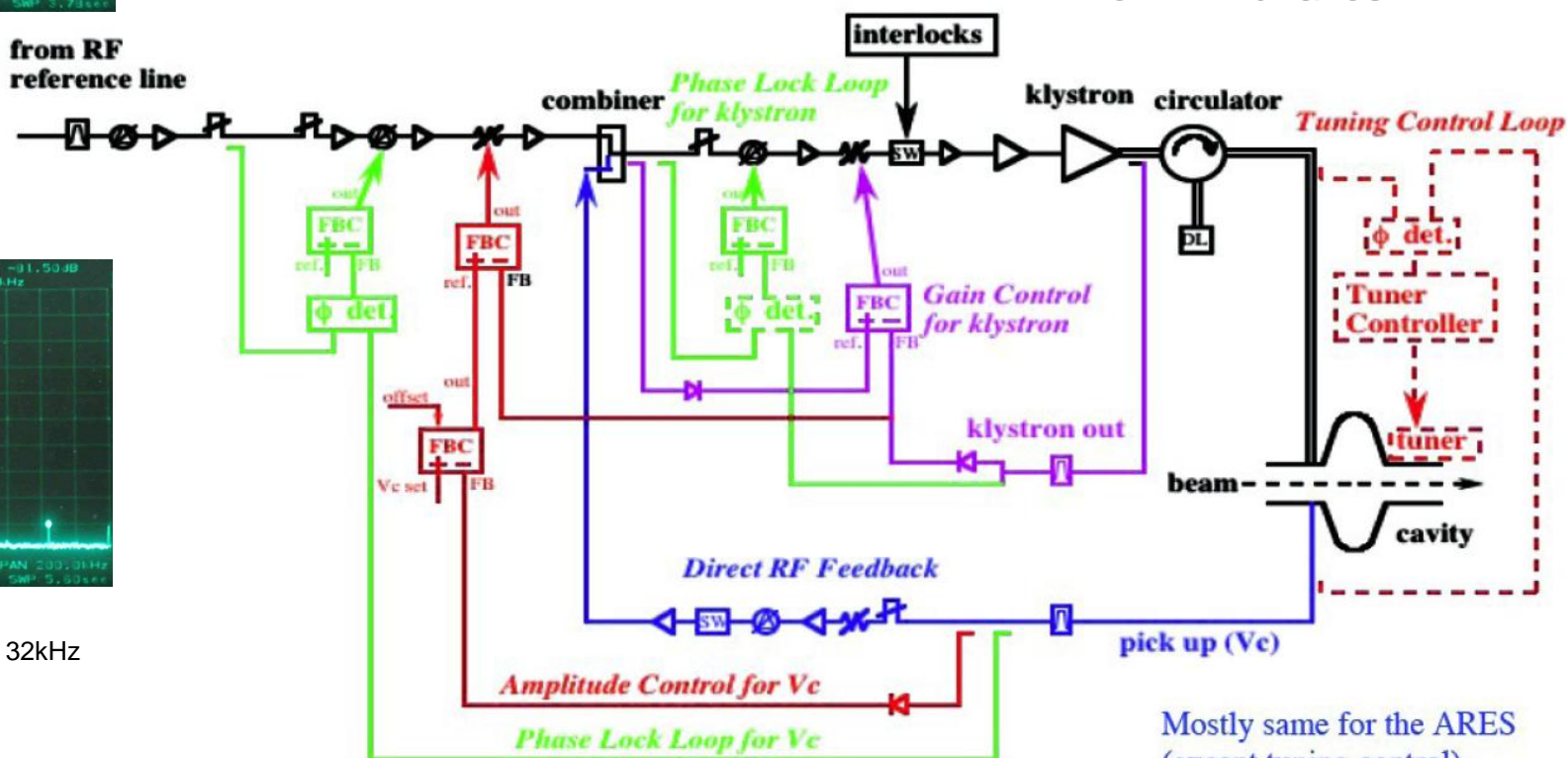
For the LHC crab application IOTs

- have sufficient power overhead to be operated in a linear regime

- have been used successfully on circular synchrotrons requiring low phase noise

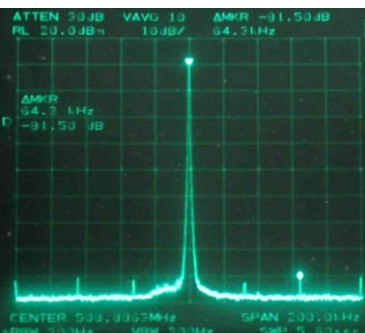- have less output sensitivity to power supply ripple than Klystrons

Something similar OK for LHC crab

Low-level RF for KEKB Superconducting cavity
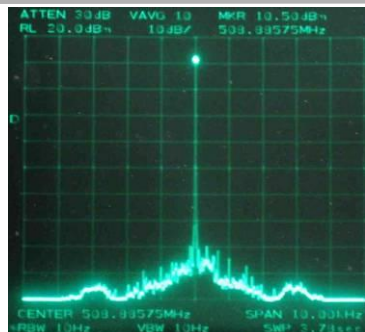
from Y. Funakoshi

Span 10 kHz

Span 200 kHz
Sideband peaks at 32kHz and 64kHz.

Mostly same for the ARES (except tuning control).

Current LLRF Activity

- Assessment and selection of 12 GHz oscillators (CLIC Crab))

- Assessment and section of 400 MHz oscillators (LHC Crab)

- Cavity phase measurement accuracy for 200 ns pulse

- Phase noise measurement and reduction (LHC Crab)

- Understanding phase noise contribution from transmission path

- DSP layout and integration (All systems using digital phase detection)