Phase monitor readout electronics

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Outline

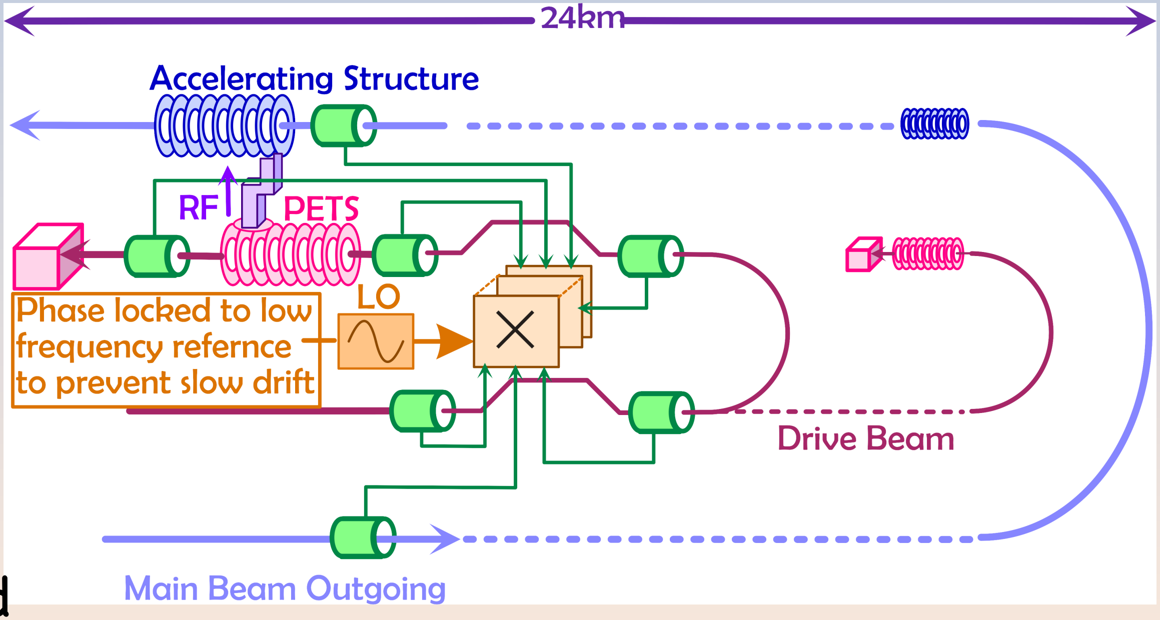
- CLIC requirements
- Problems of signal transport and detection
  - Amplitude flatness
  - Dispersion
  - Non-linearities
  - Noise
- Phase detector PCB
- Baseband processing and system layout

Review of CLIC requirements

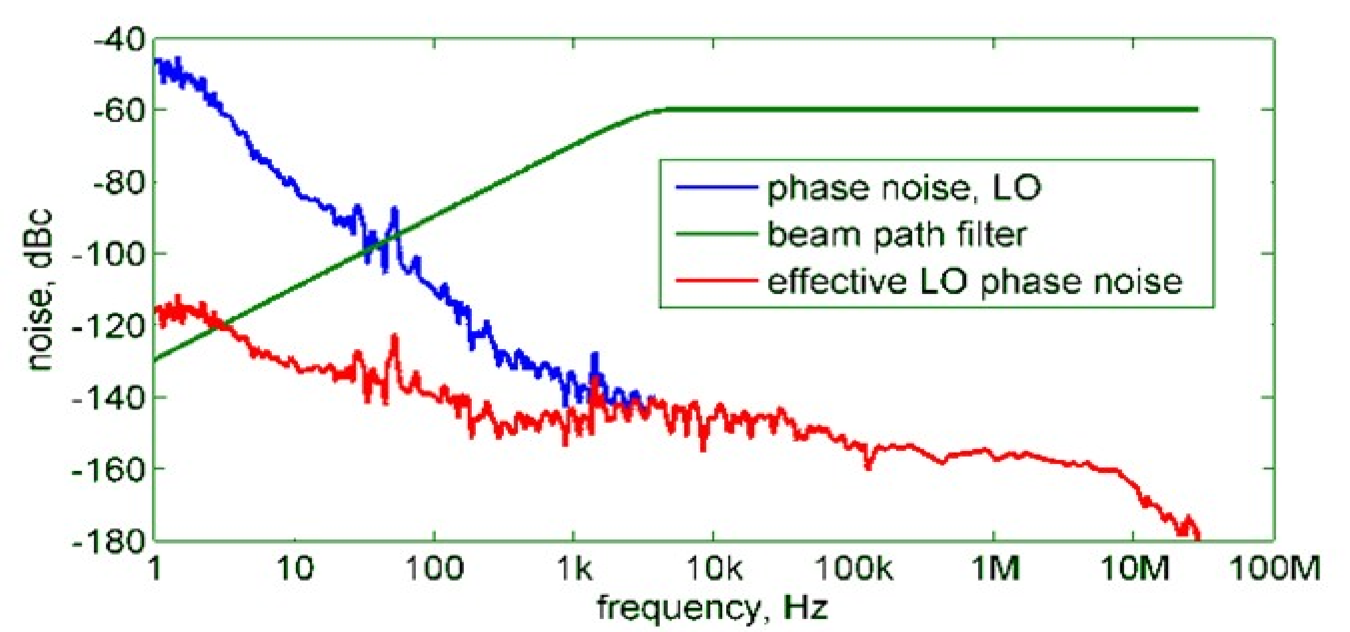
- In order to avoid luminosity loss very tight synchronization between the main beam and the accelerating RF is required.
- A phase feed-forward correction scheme has been developed to deal with eventual errors in the drive-beam before energy extraction.
- This scheme relies on very precise measurements of the drive-beam phase.
- We require a measurement of 0.1° resolution up to a bandwidth of around 50 Mhz.
- The RF delivered to the electronics can be expected to have an amplitude modulation up to 1‰.

Phase detection location in CLIC

- The phase detection will take place before the drive-beam turnarounds.
- The drive-beam will then be kicked in the chicane after the turnaround in order to change the longitudinal position of its bunches as needed.
- As a reference distribution system has not been demonstrated over these distances a scheme relying on local oscillators has also been developed



Local Oscillator performance



- Since we need to keep time only for the return trip on the main beam (160 μs) the noise contribution from the local oscillator is effectively filtered at low frequencies
- Integrated phase noise is around 5 fs (0.02 °) at 12 GHz.

AM-PM conversion

- What do we require in order to treat the RF containing phase information with sufficiently low distortion for this highly precise measurement?

Carrier	Phase Modulation (quadrature)	Amplitude Modulation (inline)
$\sin(\omega_0 t)$	$\varphi_0 \sin(\omega_d t)\cos(\omega_0 t)$	$a\cos(\omega_d t)\sin(\omega_0 t)$

$$-\frac{\varphi_0}{2}\{\sin([\omega_0+\omega_d]t)-\sin([\omega_0-\omega_d]t)\}$$

$$\frac{a}{2}\{\sin([\omega_0+\omega_d]t)+\sin([\omega_0-\omega_d]t)\}$$

Amplitude flatness

- Suppose we have a device that affect the amplitude of the two frequencies of an amplitude modulated signal differently. (Poor flatness)

$$a_1 \sin([\omega_0+\omega_d]t)+a_2 \sin([\omega_0-\omega_d]t)$$

Rewrite as sums and diffs

$$\frac{a_1+a_2}{2}\sin([\omega_0+\omega_d]t)+\frac{a_1+a_2}{2}\sin([\omega_0-\omega_d]t)$$

Amplitude Modulation

$$+\frac{a_1-a_2}{2}\sin([\omega_0+\omega_d]t)-\frac{a_1-a_2}{2}\sin([\omega_0-\omega_d]t)$$

Phase Modulation

- Phase modulation thus induced scales with the modulation depth and the defects in device amplitude flatness.
- There is a similar phase to amplitude conversion, which will scale the phase modulation by some amount

Dispersion (1)

- Suppose we have a device that is dispersive, so that the frequency components of an amplitude modulation have different transit times

$$\sin(\omega_0 t)+a\{\sin([\omega_0+\omega_d][t+T_m(\omega_d)+T_d(\omega_d)])+\sin([\omega_0-\omega_d][t+T_m(\omega_d)-T_d(\omega_d)])\}$$

- Rewrite

$$\sin(\omega_0 t)$$

$$+a\cos(T_m\omega_0+T_d\omega_d)\cos(T_m\omega_d+T_d\omega_0+\omega_d t)\sin(\omega_0 t)$$ Amplitude Mod.

$$+a\sin(T_m\omega_0+T_d\omega_d)\cos(T_m\omega_d+T_d\omega_0+\omega_d t)\cos(\omega_0 t)$$ Phase Modulation

- The AM-PM conversion is thus $a\sin(T_m\omega_0)$ with $\omega_0 \gg \omega_d$ that is, proportional to the size of the amplitude modulation and the average transit time difference of the two modulation components

Dispersion (2)

- The resulting modulation term

  $$\cos(T_m \omega_d + T_d \omega_0 + \omega_d t) \approx \cos(T_d \omega_0 + \omega_d t)$$

  causes distortion of the signal envelope

- T_d is of course dependent on the modulation frequency ω_d. The linear part of $T_d(\omega_d)$ causes only a time-shift of the modulation, any non-linear part distorts the signal

- The phase modulation term works exactly the same way. That is, some phase modulation will turn into amplitude modulation, and some distortion of the phase signal will occur

AM-PM, some numbers

- Devices can be specified to 0.1dB flatness, but not 0.01dB. (Influence of connectors and cable become too large for reliable measurements to be made)
- With 0.1 dB flatness, we get 3.3×10^{-4} ° per permille of amplitude modulation
- 0.1 dB flatness will scale a phase modulation by 0.5%
- At 12 Ghz, with 1‰ amplitude modulation, we get 0.004° per ps of transit time difference
- Since these errors can pile up, it is important to consider all bits of the signal transport chain. (Waveguides, cables, filters, etc.)

Non-linearities

$$A\sin(\omega_1 t)+B\sin(\omega_2 t)$$

$$\Rightarrow A\sin(\omega_1 t)+a_2 A^2\sin^2(\omega_1 t)++a_3 A^3\sin^3(\omega_1 t)+\ldots$$

$$+B\sin(\omega_2 t)+b_2 B^2\sin^2(\omega_2 t)+b_3 B^3\sin^3(\omega_2 t)+\ldots$$

$$+A\,B\,c_{1,1}\sin(\omega_1 t)\sin(\omega_2 t)+A^2 B\,c_{2,1}\sin^2(\omega_1 t)\sin(\omega_2 t)+A\,B^2 c_{1,2}\sin(\omega_1 t)\sin(\omega_2 t)$$

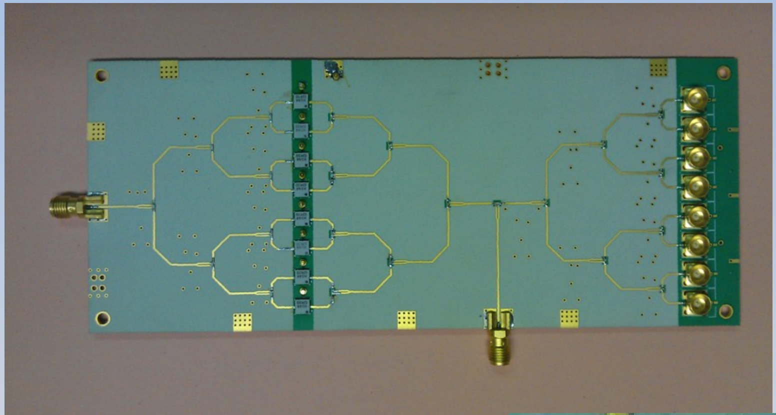
$$\omega_{1,}\,\omega_{2,}\,2\omega_{1,}\,2\omega_{2,}\,2\omega_1-\omega_{2,}\,\omega_1-2\omega_{2,}\ldots$$

- By device non-linearities we get a large set of frequencies in the output that were not in the input.
- These grow with the amplitude to the power of term order of the input signals.
- By lowering input power we can have a smaller fraction of the output of these frequencies compared to the wanted ones

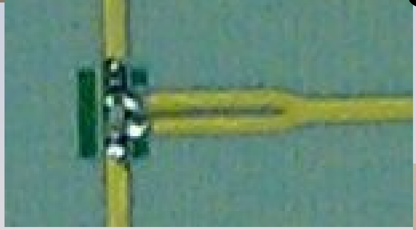
Non-linearities and noise

- In phase detection devices, there are in particular a second order term that mixes to baseband and is indistinguishable from real phase.
- We must thus lower input power until this contribution becomes small enough.
- This reduces our signal to noise ratio.
- Recover better SNR by using multiple devices in parallel and averaging their output.
- We get a noise improvement of square root of N for N devices.

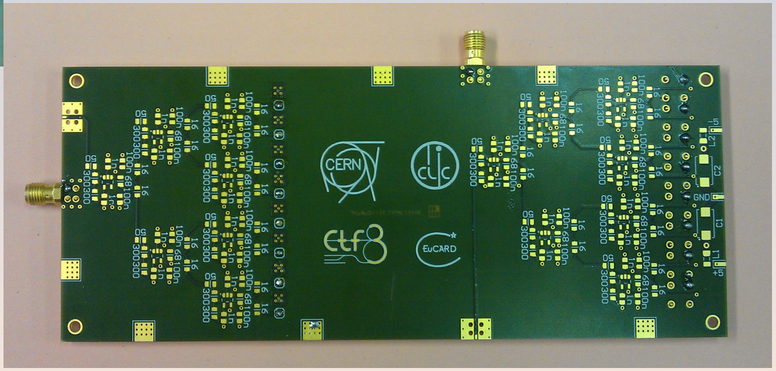
Phase detector PCB



- Phase detector PCB has been fabricated and partially populated.
- The high frequency side consists of a set of 12 GHz power splitters

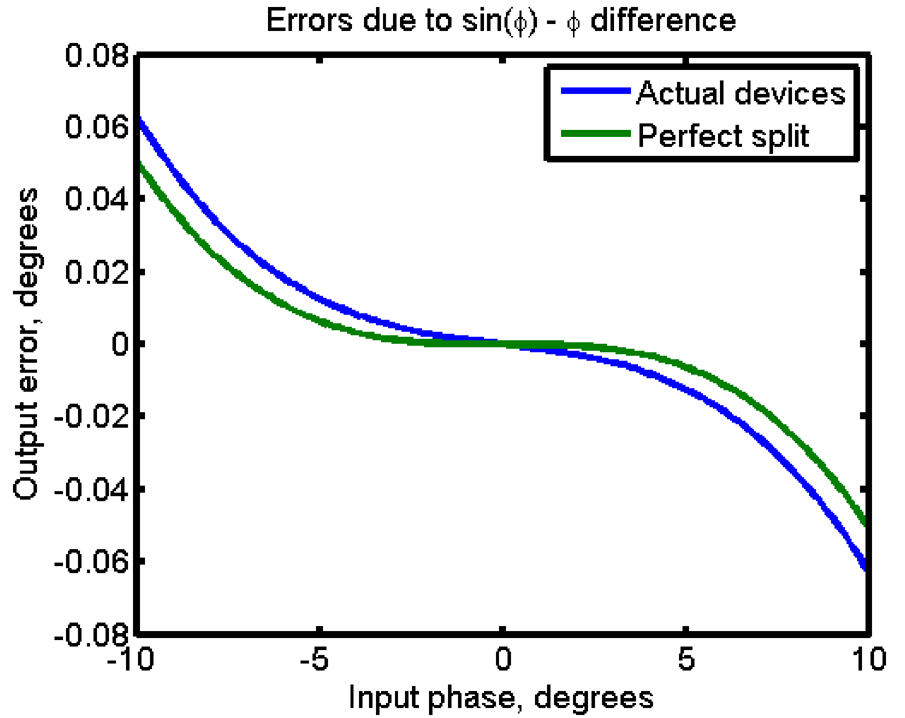


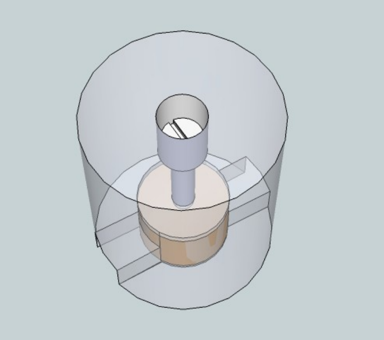
- Performance measurements of the high frequency side have been made.



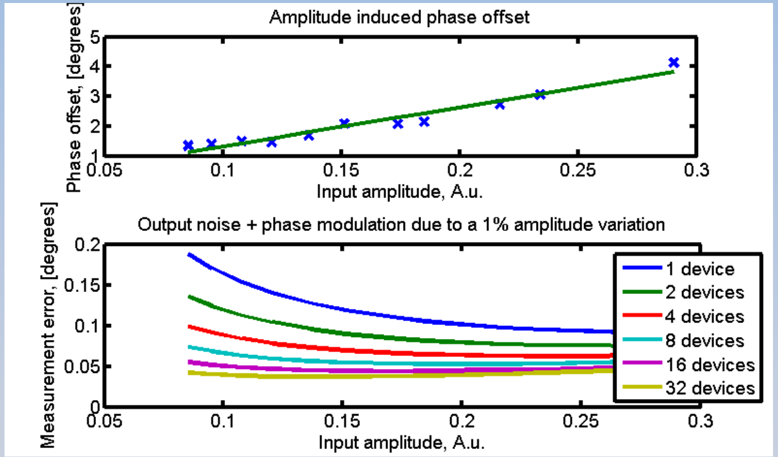
Amplitude and phase imbalance

- Amplitude balance between the splitters were found to be 1.1 dB.
- Phase balance was ±4°
- These errors have only a negligible impact on electronics performance compared to ideal power splitters
- The phase balance could be corrected by installing small, capacitively coupled phase shifters



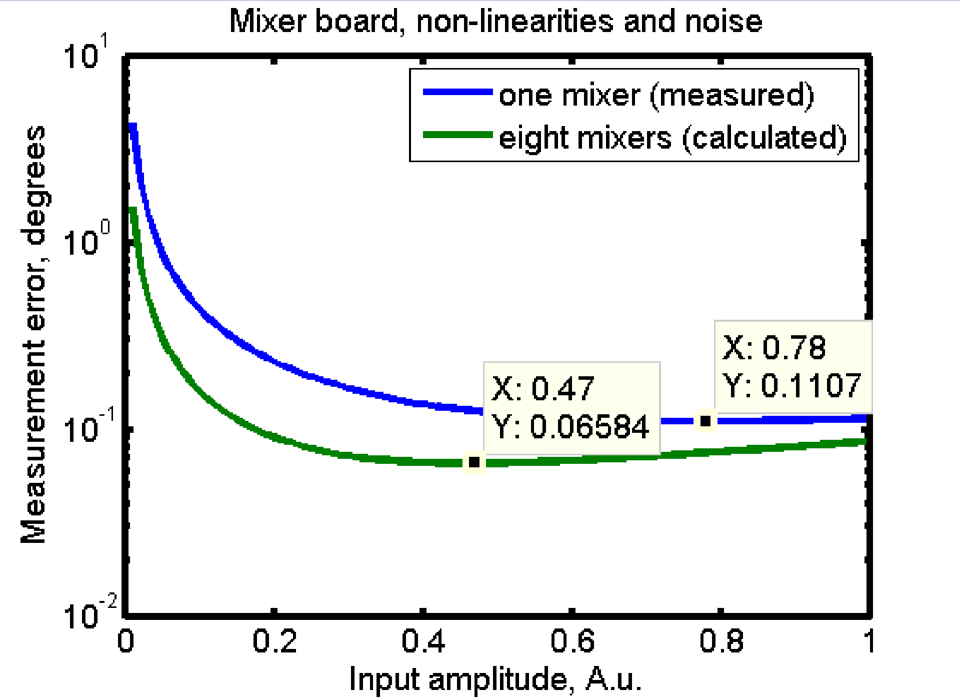


Non-linearity and noise performance



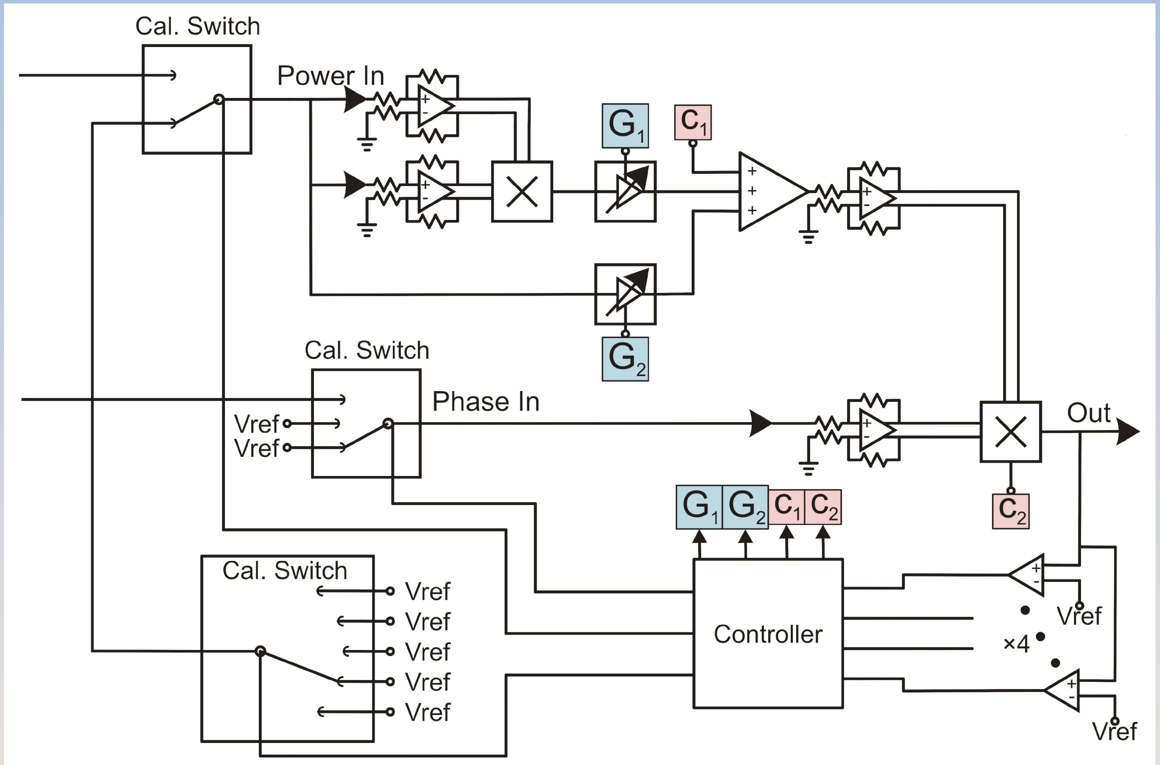
- Mixer non-linearity in the form of AM to PM conversion increases with input amplitude.
- Signal to noise ratio does the opposite

- Somewhere there is an optimum input amplitude for a particular device.
- By averaging several devices we can improve signal to noise ratio.



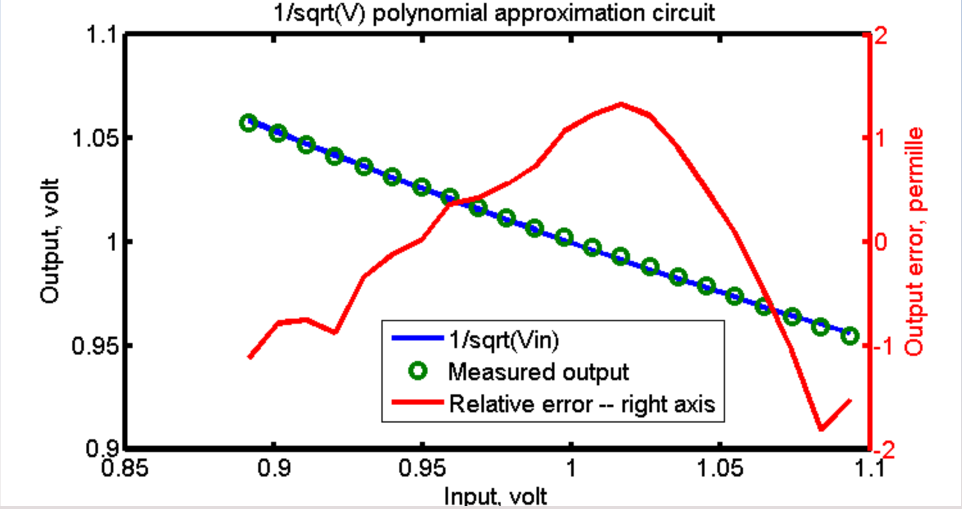
Post-mixer processing

- Though the expected amplitude variation within the pulse is small, we must have the possibility of accepting some range of input amplitudes. Therefore we must be able to divide out the amplitude.



Analog processor performance

- The polynomial approximation circuit can be calibrated to well follow a 1/sqrt(V) curve.



CTF3 tests

- The phase monitor electronics will be equipped with its own calibration circuit.
- Slow feedback paths (in red) tracks pulse to pulse phase and amplitude variations to keep within the range of the electronics.