CLIC Crab Synchronisation

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CLIC Workshop Meeting, CERN

7th March 2017

Enhanced European Coordination for Accelerator Research & Development

Outline

CLIC requirement

- CLIC Crab cavity synchronization requirements
- RF Distribution options
- Planned solution for CLIC

Microwave Interferometry

- Test measurement and control scheme
- Signals with phase noise
- Estimation of phase measurement precision
- Results on phase measurement precision (problems encountered)

Development of RF front end, data processing

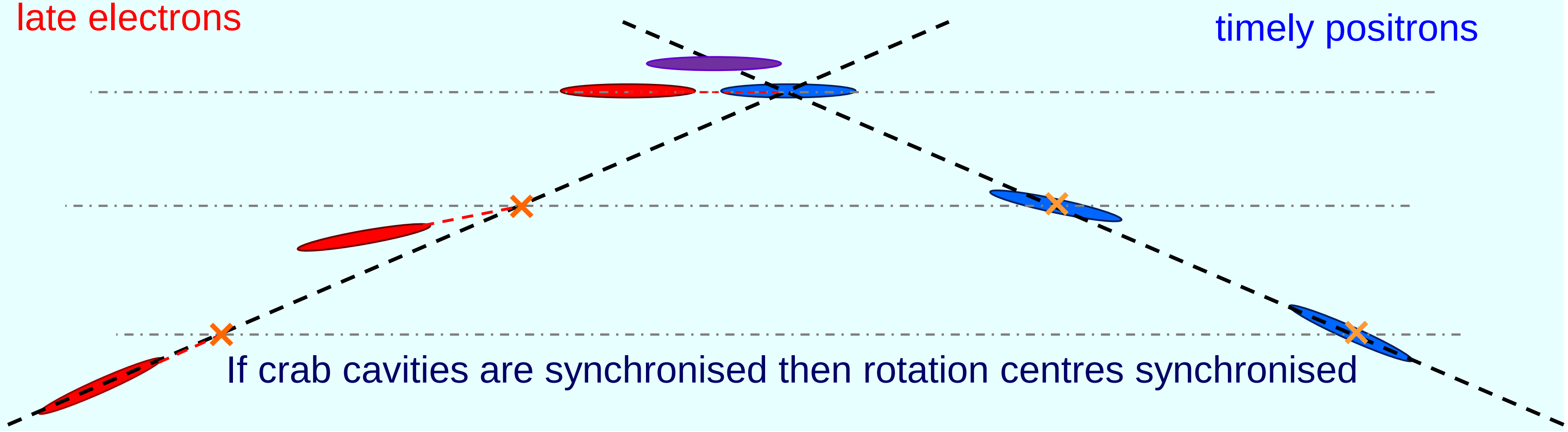
- Digital sampling and control
- Test boards
- Calibration and correction

Phase shifters

- Requirement and design
- Actuation
- Performance

Achievements

Synchronisation Requirement



If crab cavities are not synchronised then they completely miss each other

Cavity to Cavity Phase synchronisation requirement (excluding bunch attraction)

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

Target max. luminosity loss fraction S	f (GHz)	σ_x (nm)	θ_c (rads)	ϕ_{rms} (deg)	Δt (fs)	Pulse Length (μs)
0.98	12.0	45	0.020	0.0188	4.4	0.156

RF Distribution Options

Option 1:

Single klystron with high power RF distribution to the two crab cavities.

Klystron phase jitter travels to both cavities with identical path lengths.

BUT

Requires RF path lengths to be stabilised to 1 micron over 40m.

Option 2:

Klystron for each cavity synchronised using LLRF/optical distribution.

Femto-second level stabilised optical distribution systems have been demonstrated (XFELs).

BUT

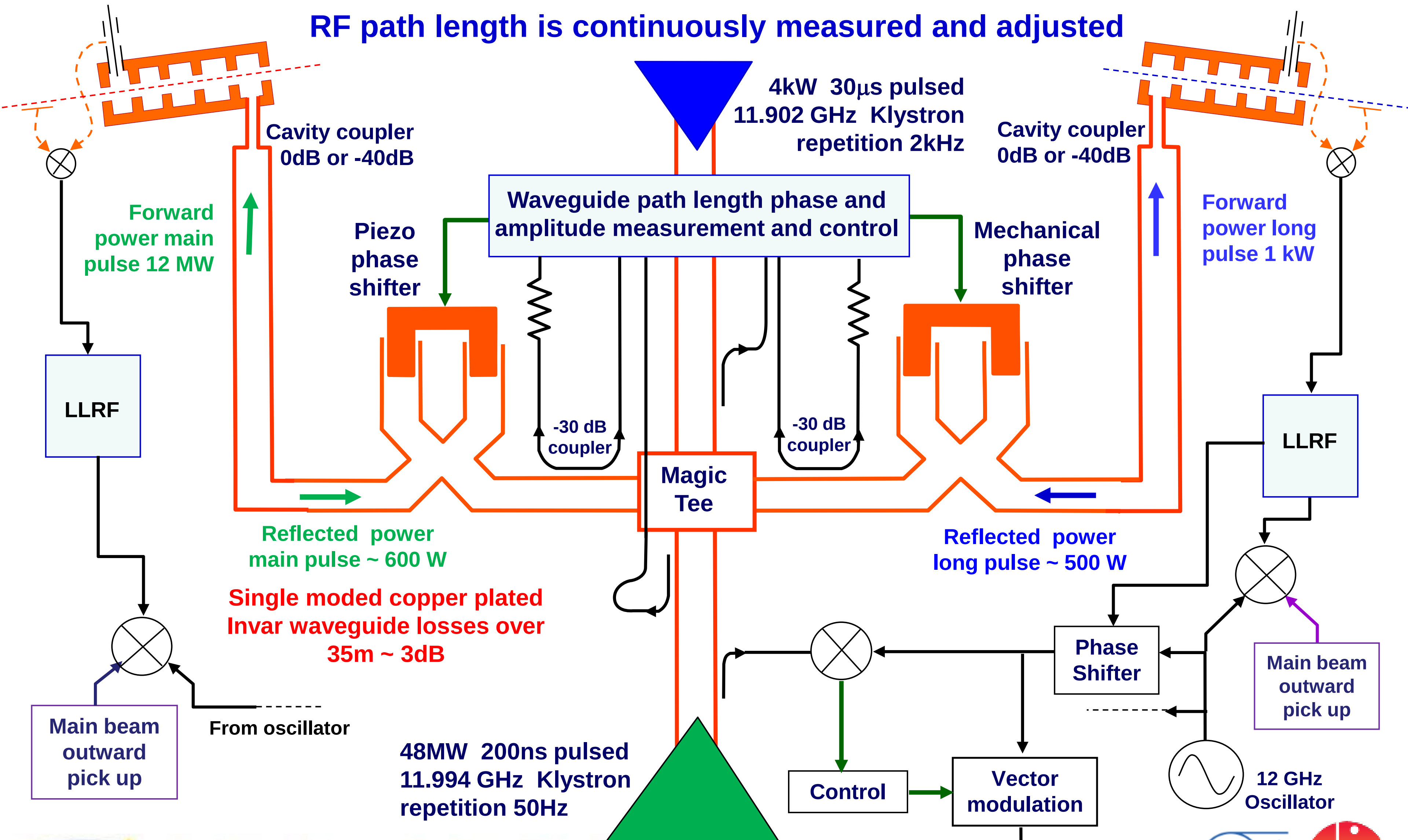
Requires klystron output with integrated phase jitter <4.4 fs.

Lancaster University

CLIC Synchronisation Proposal

The Cockcroft Institute of Accelerator Science and Technology

RF path length is continuously measured and adjusted



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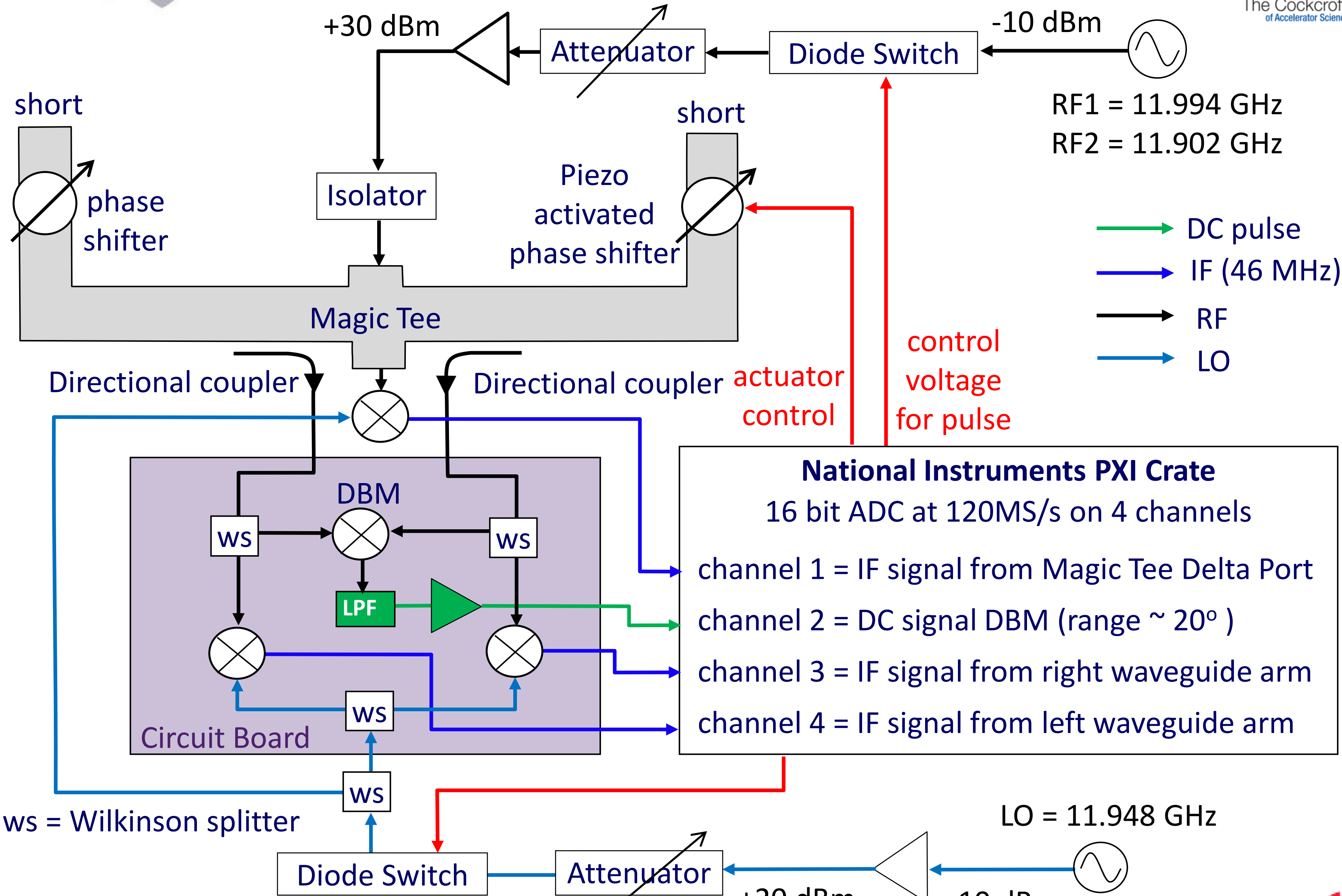
CERN CLIC

Feasibility Measurement Scheme



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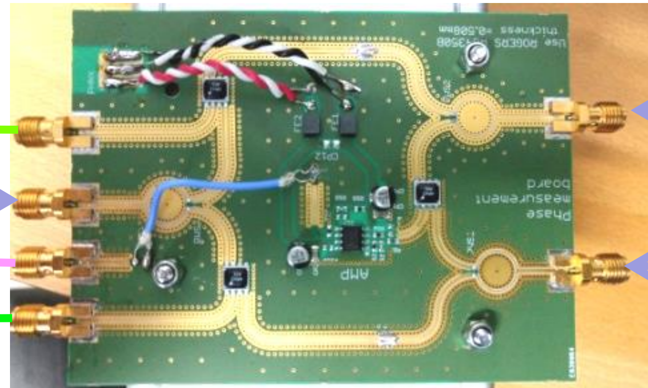
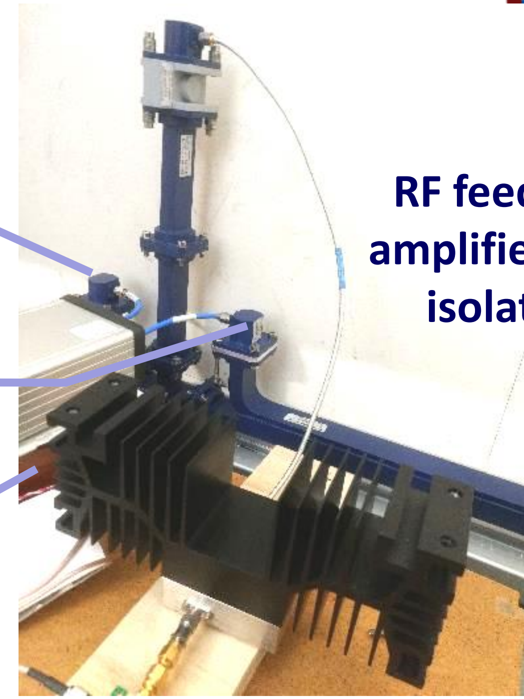
Electronics



Mixing PCB



RF feed via amplifier and isolator

From Magic Tee

NI PXI Spec.:

- 16bit ADC, 120MS/s, 4-channel digitizer
- 2.2GHz Celeron module with FlexRIO FPGA module

National Instruments PXI crate

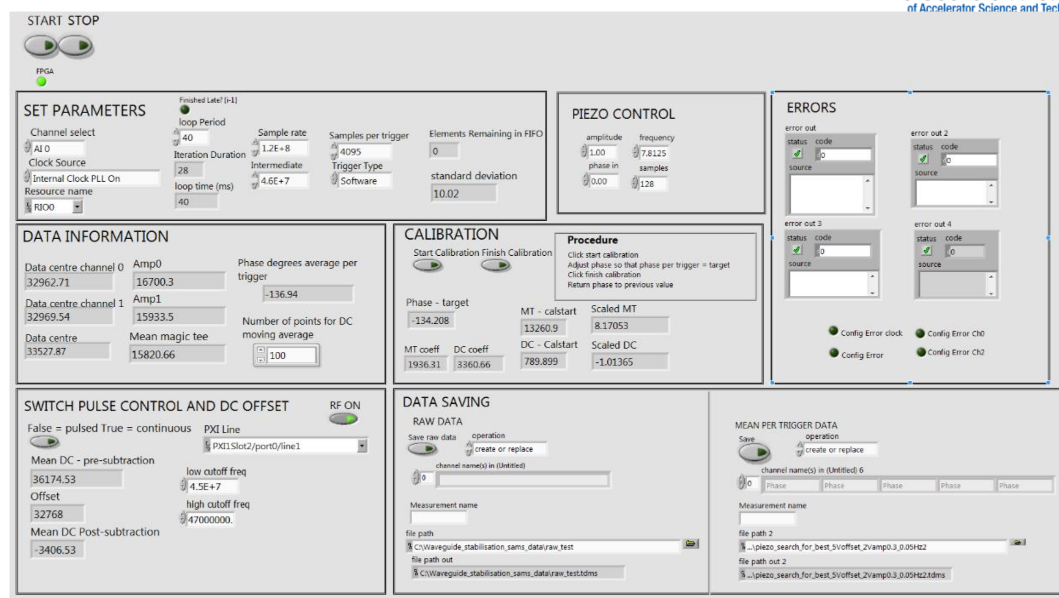
Pin diode switch to pulse RF

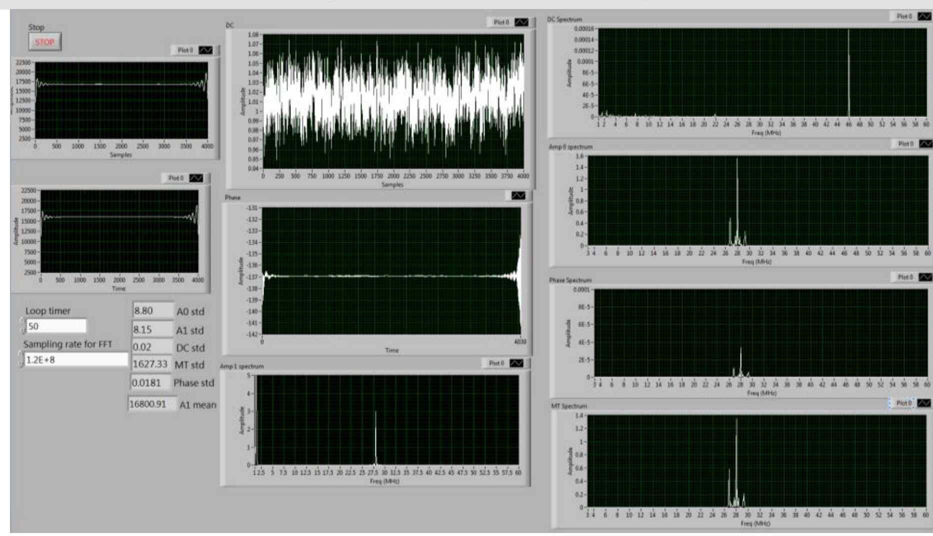
Locked DI Instruments Oscillators ($700)

Digital Sampling Hardware

LabVIEW used for acquisition

- **Front panel allows for control of calibration, pulsing timings, piezo actuator and ADC clocking frequency.**
- **GUI on host computer allows for real time viewing of signal spectrums**





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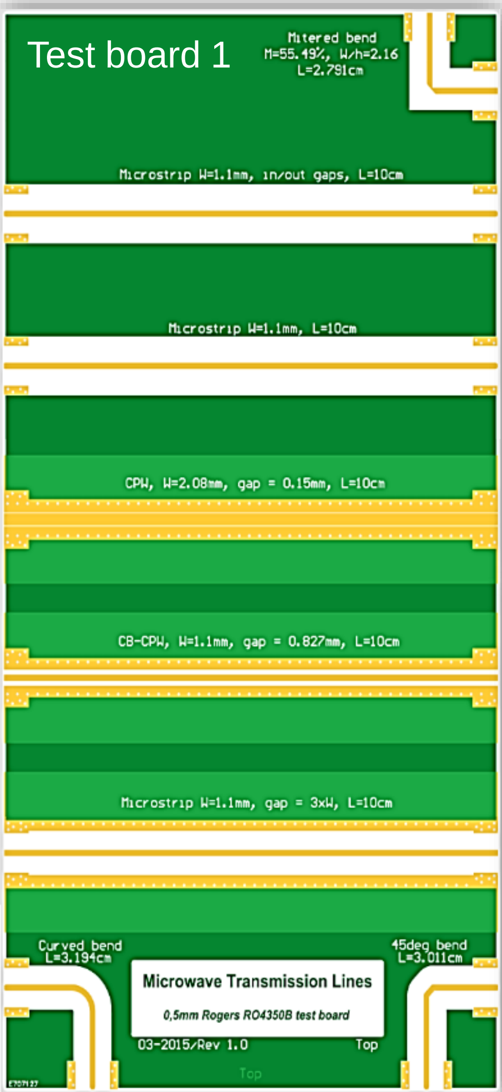
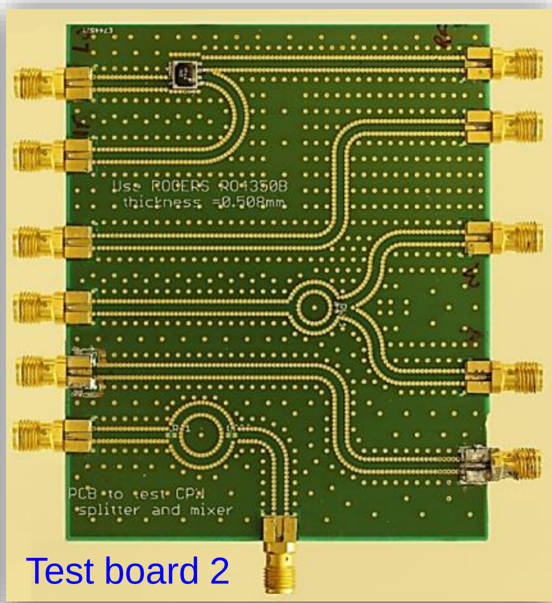
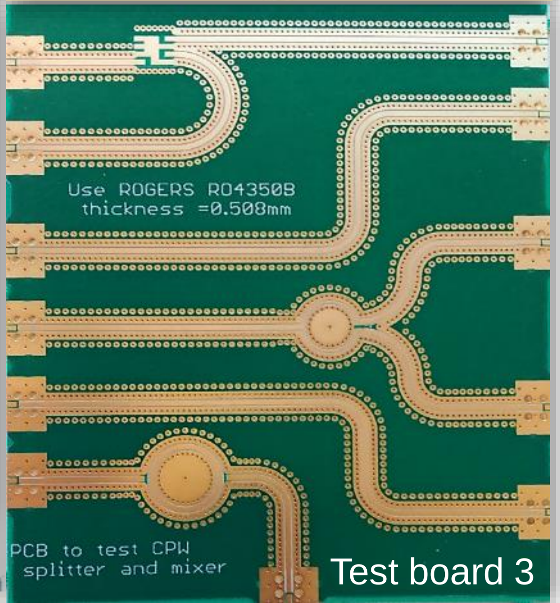
Test Boards



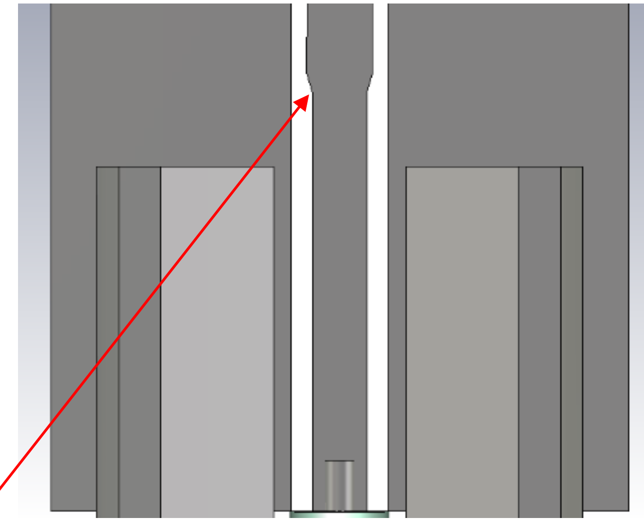




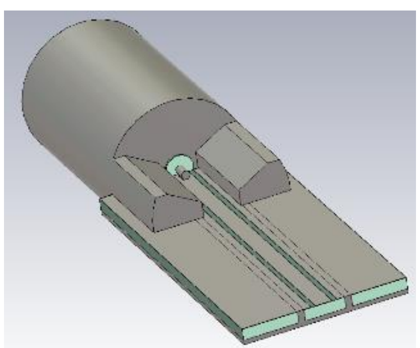
- Multiple **test boards** have been developed to achieve optimum performances at 10-12GHz.
- Test board 1 examined:
  - ❑ Choice of optimum transmission line (Microstrip, CPW, GCWP, Stripline, …)
  - ❑ Impedance matching and transmission responses
  - ❑ SMA connector type, bends, etc.
  - ❑ And measured wavelength
- Test boards 2 & 3 have:
  - ❖ A mixer
  - ❖ 2 TL lines differing in length by λ/4
  - ❖ A Wilkinson splitter
  - ❖ A ring resonator
- Test boards 2 & 3 examined:
  - ❑ The 'real' PCB ε_r
  - ❑ The effect of soldermask
  - ❑ Improved pads, via locations, copper-to-edge, etc.

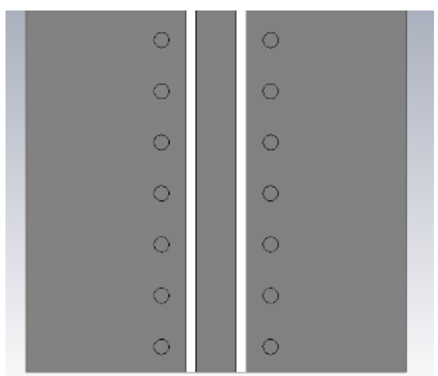
Connector Simulations

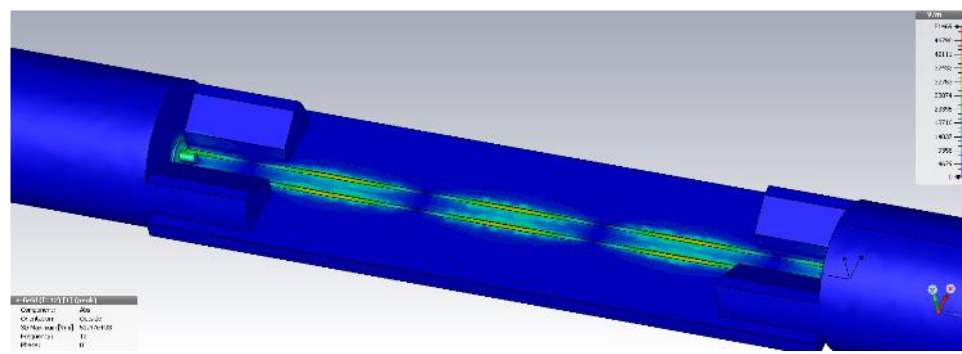
- Excessive reflection from test tracks
- CST simulations model 3D configuration of connectors , tracks and via positions.
- Track width and taper optimised to match connector and launch pad minimising reflection at operating frequency



Track width taper at launch pad

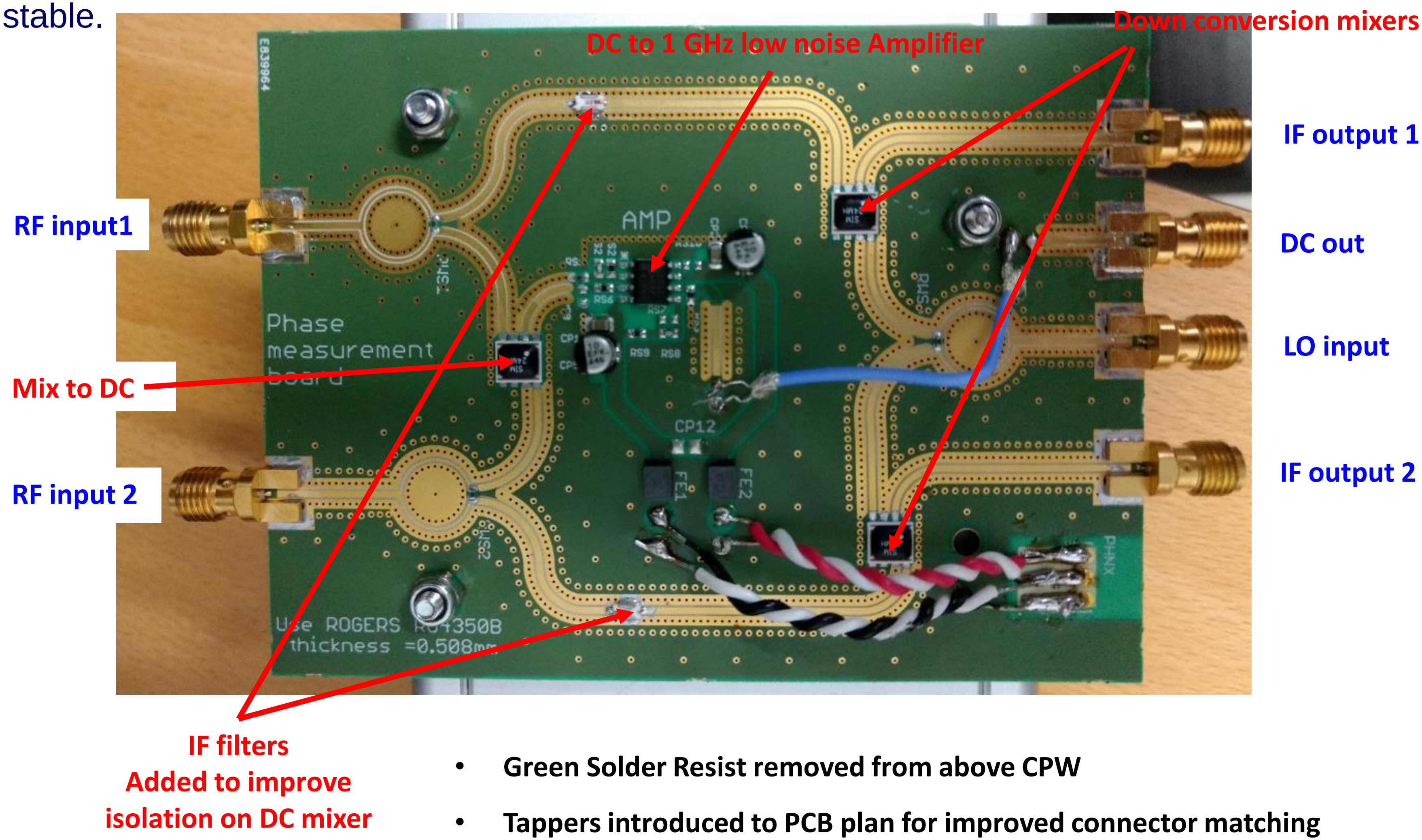






New Board 2016

The phase board must split signal as with minimal reflection, track lengths are careful set so that reflections cancel. The board must be compact and dimensionally stable.



- **Green Solder Resist removed from above CPW**
- **Tappers introduced to PCB plan for improved connector matching**

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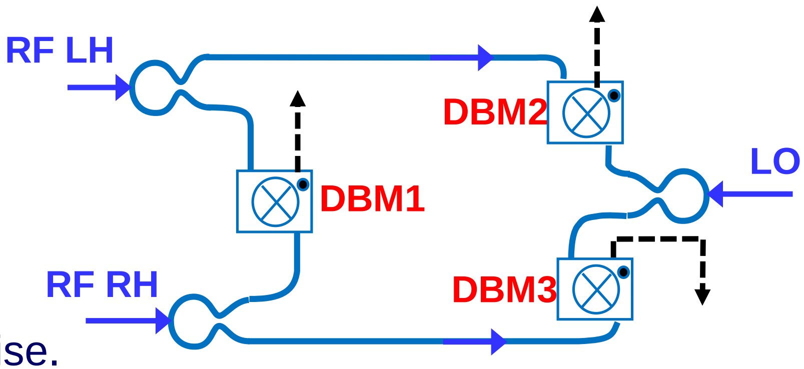
Notes on Synchronisation

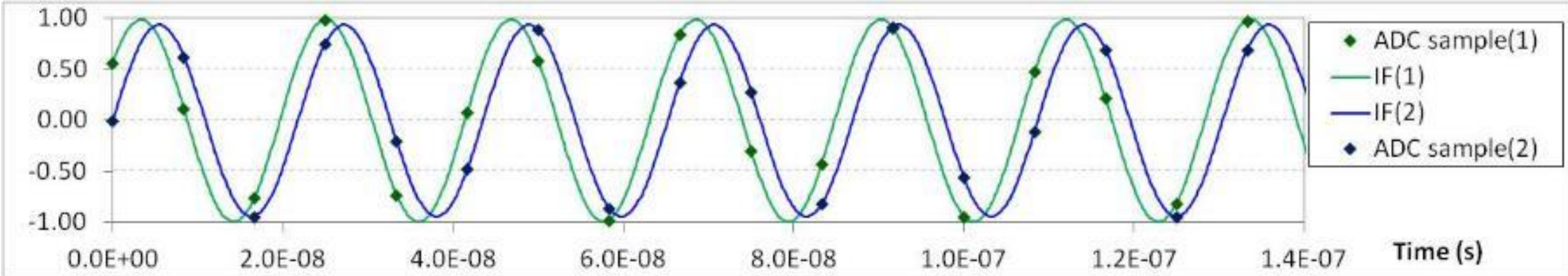
DBM = double balanced mixer



- For synchronisation DBM1 controlled to zero.
- Measurement independent of oscillator phase noise.
- Corrections on phase measurements require knowledge of amplitudes.
- Very small 'd.c.' voltage pulses lasting the length of the RF pulse must be measured.
- Offsets can be determined between pulses and then removed.
- High amplification on DBM1 means that 360° cannot be measured (PXI input limitation).
- Direct sampling of DBM2 and DBM3 allows:-
  - 360° to be determined
  - course phase variation on each arm to be monitored
  - phase differences to be brought to range of DBM1
  - calibration of DBM1 output – tells us how close to zero we are
  - monitoring separate arms of interferometer needs RF and LO to be locked

Phase Determined from IF

Choice of 16 bit 120 MS/s ADC forced use of asynchronous sampling



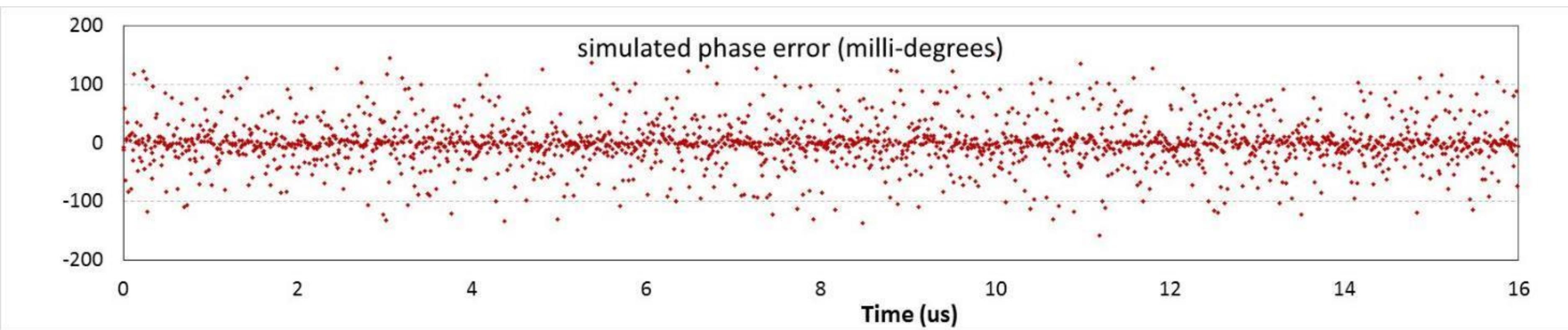
Deduce phase using

$$\phi = \tan^{-1}\left(\frac{y_1(n) - y_1(n+1)}{y_1(n) + y_1(n+1)} C\right) - \tan^{-1}\left(\frac{y_2(n) - y_2(n+1)}{y_2(n) + y_2(n+1)} C\right)$$

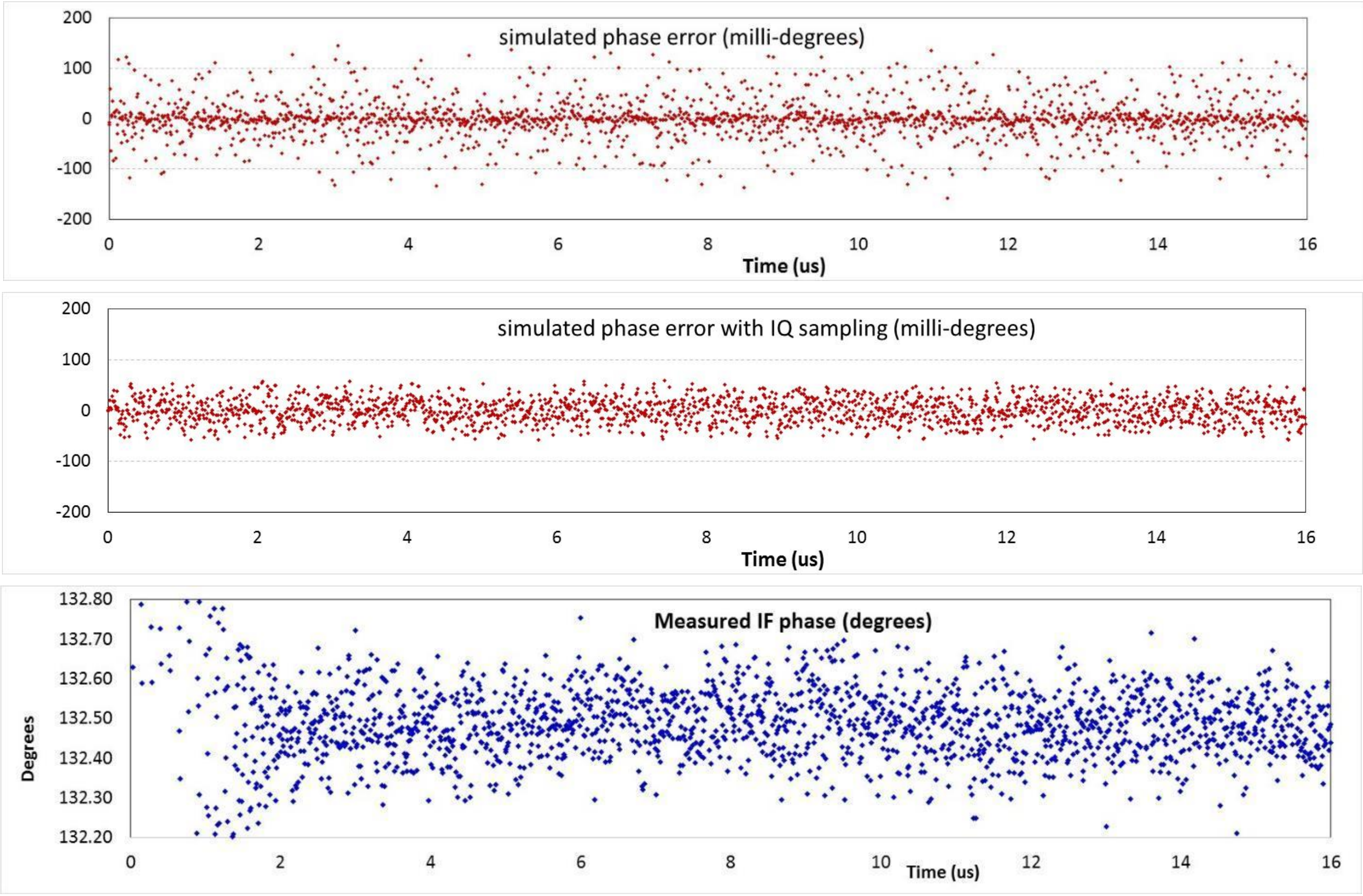
where $C = \cot\left(\pi \frac{f_{IF}}{f_{sample}}\right)$

Simulated ADC errors (assumes noiseless input to the ADC)

ADC Aperture jitter = 80 fs (rms) and noise = random +/-15



Expected verses Actual Performance for IF

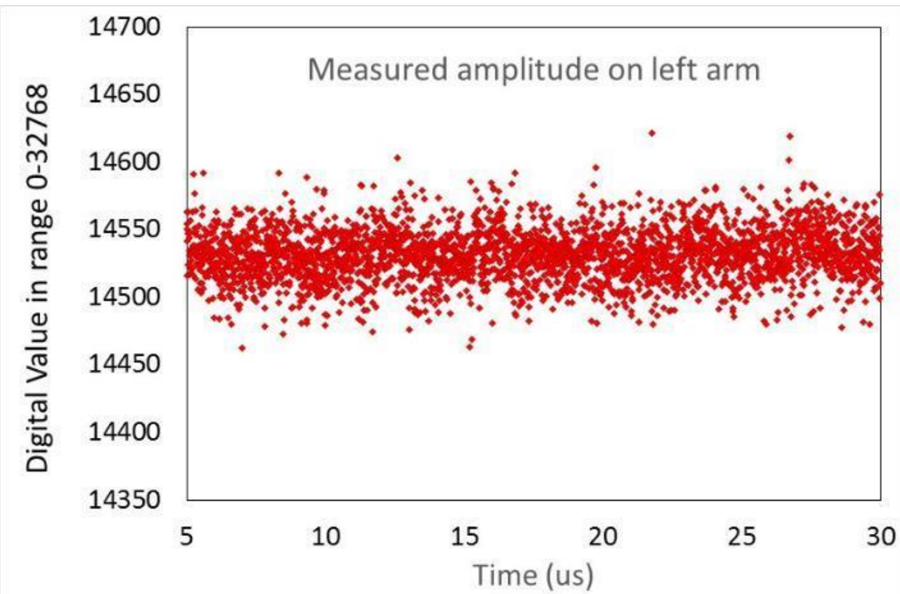


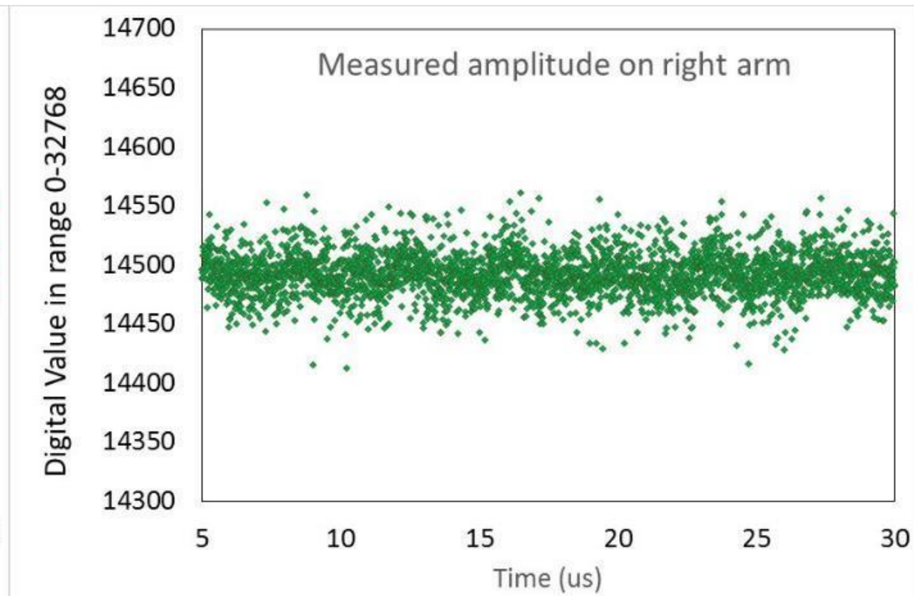
Amplitude Determined from IF

Amplitude determined from adjacent sampled points y_o and y_1 on IF waveform using

$$A = 0.5\sqrt{c_f^2(y_0+y_1)^2 + s_f^2(y_0-y_1)^2} \qquad \frac{1}{c_f} = \cos\left(\pi\frac{f_{IF}}{f_{sample}}\right) \qquad \frac{1}{s_f} = \sin\left(\pi\frac{f_{IF}}{f_{sample}}\right)$$

Originally notch filters are applied to the raw data to remove the IF frequency of 46 MHz and other spurious frequencies





Expected spread on measured values ~ 35, actual ~ 60, (left slight more noisy than right)

Magic Tee - Amplitude Dependence of Phase

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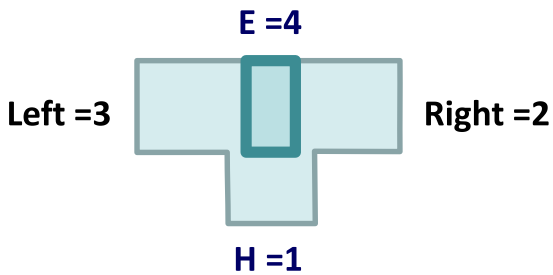
The interferometer launches on port 1 has a return signals on ports 2 and 3 with slightly different amplitudes and phase.
We require phase difference $\theta_3 - \theta_2$



For the perfect Magic Tee we have

$$\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ A_2(\cos\theta_2 + j\sin\theta_2) \\ A_3(\cos\theta_3 + j\sin\theta_3) \\ 0 \end{bmatrix} = \begin{bmatrix} (A_2\cos\theta_2 + A_3\cos\theta_3) + j(A_2\sin\theta_2 + A_3\sin\theta_3) \\ 0 \\ 0 \\ (A_2\cos\theta_2 - A_3\cos\theta_3) + j(A_2\sin\theta_2 - A_3\sin\theta_3) \end{bmatrix}$$

Measuring amplitude V_4 from port 4 we have

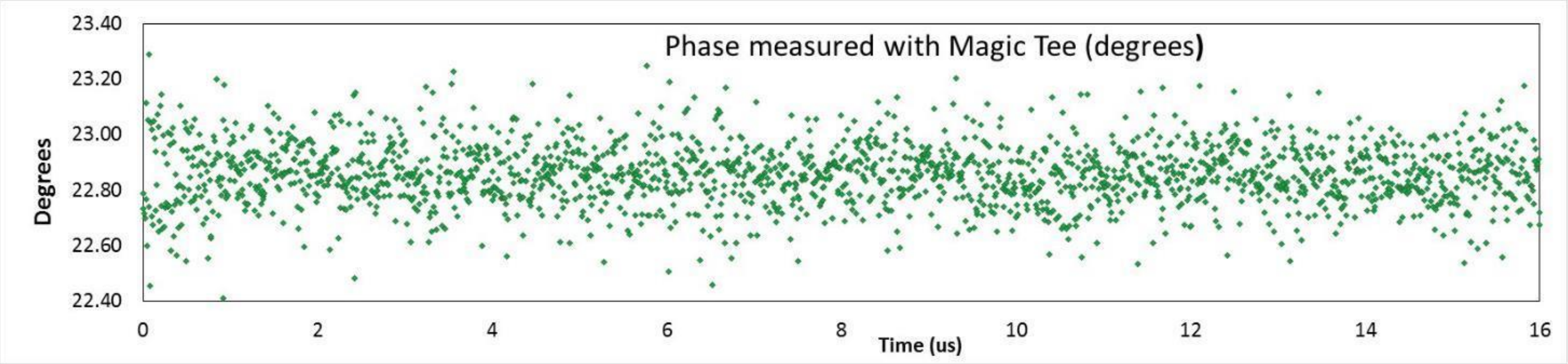
$$\theta_2 - \theta_3 = 2\sin^{-1}\sqrt{\frac{V_4^2 - (A_2 - A_3)^2}{4A_2A_3}}$$

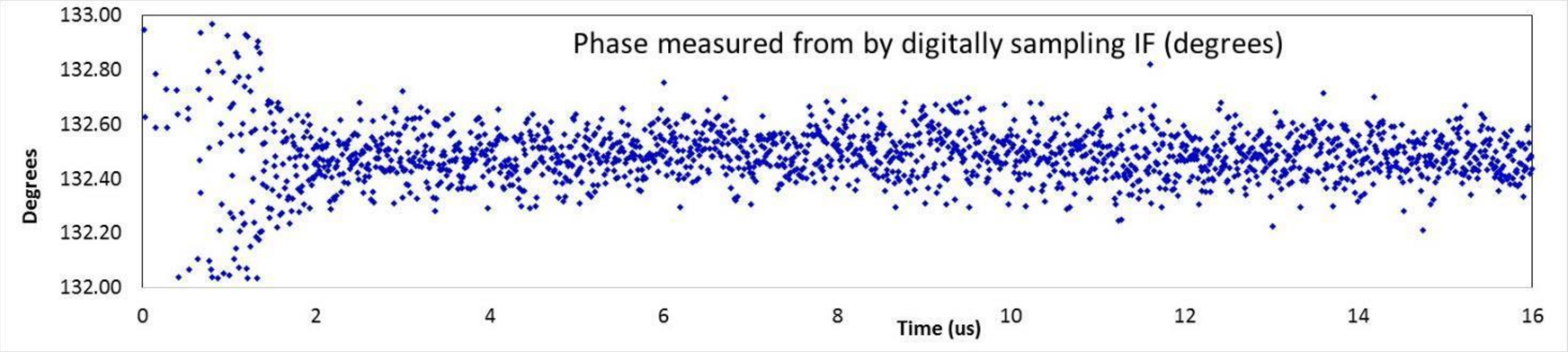
The phase difference between ports 2 and 3 depends on input amplitudes to the ports as well as output on port 4.

The accuracy of determining the phase difference between returning signals on the left and right arms of the interferometer depend on accuracy of our measurement of amplitude

Magic Tee and IF Measurements Compared

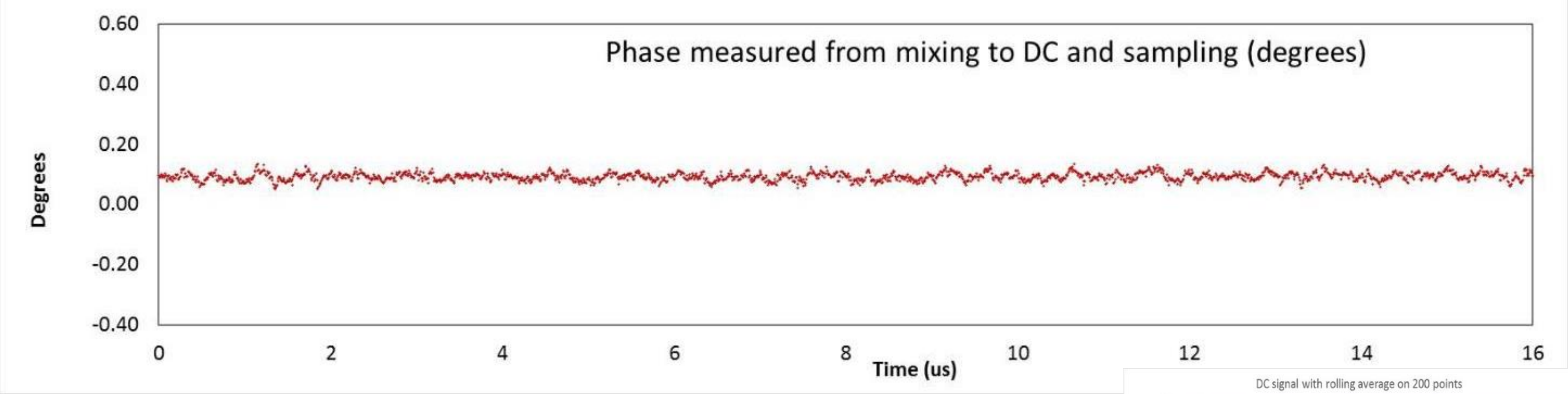
Vertical range is 1 degree for both graphs

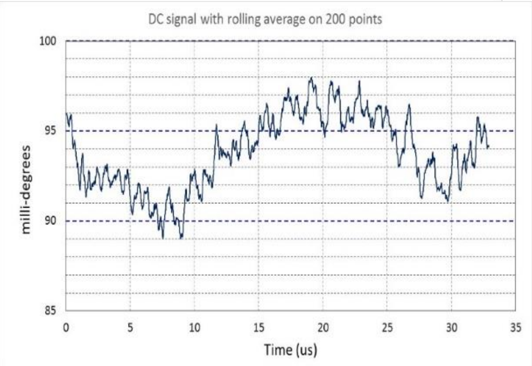




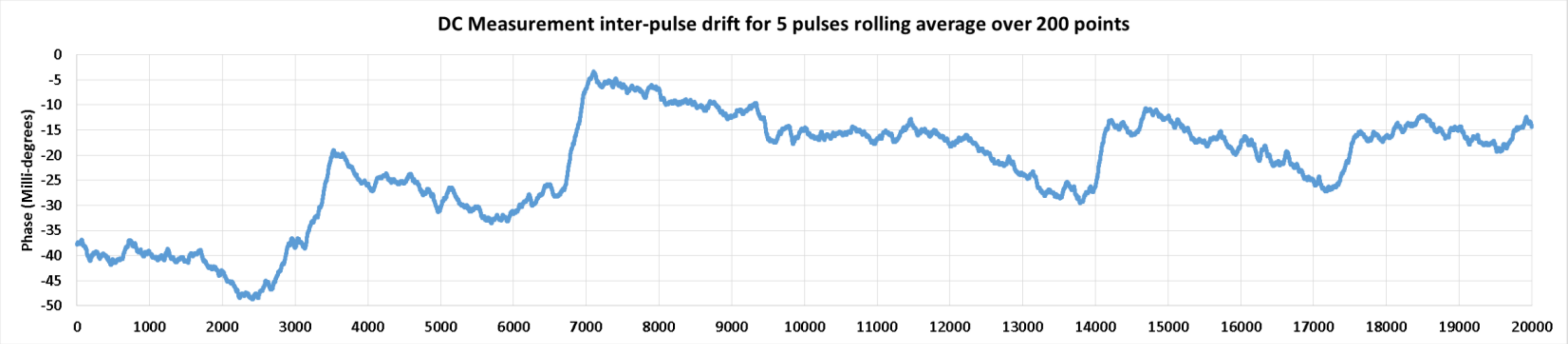
The Magic Tee measurements did not use the phase board and SIM24 MH+ mixer, this might explain the slightly high level of noise.

DC Measurement

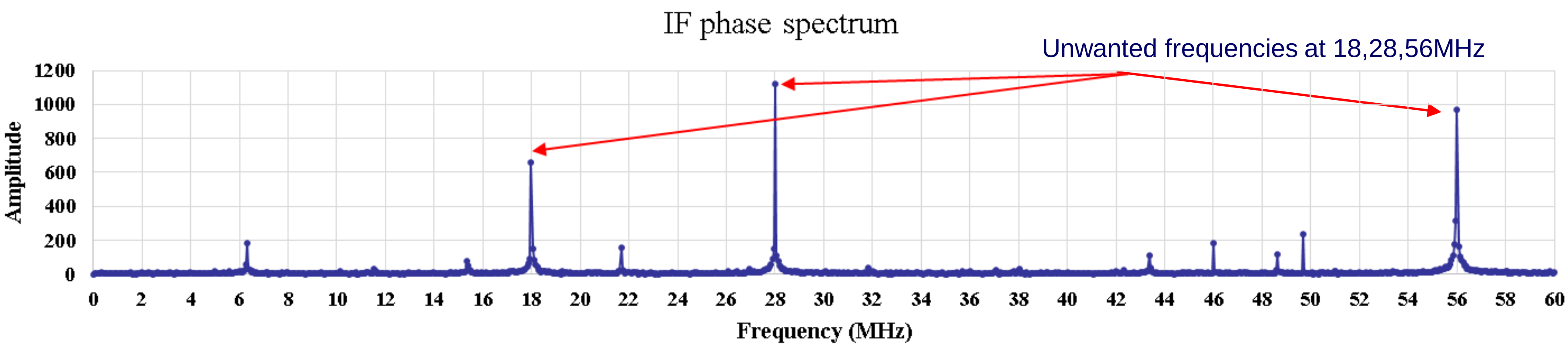


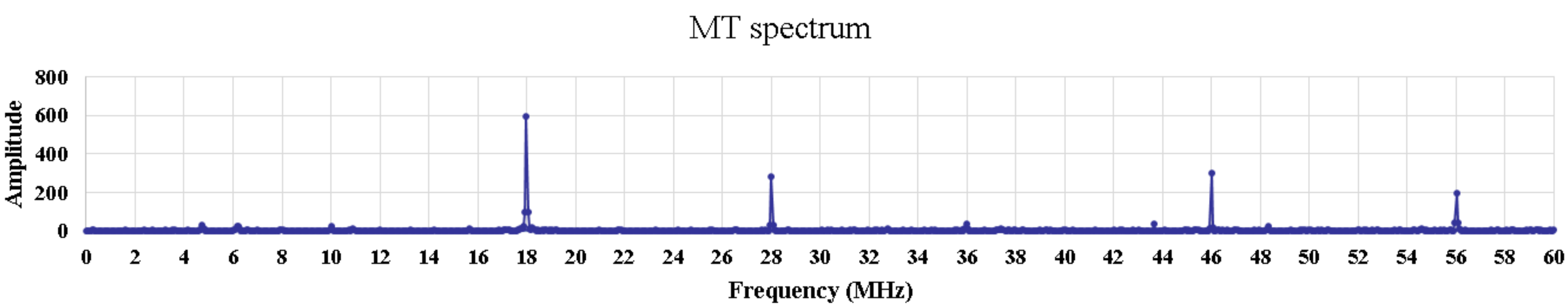


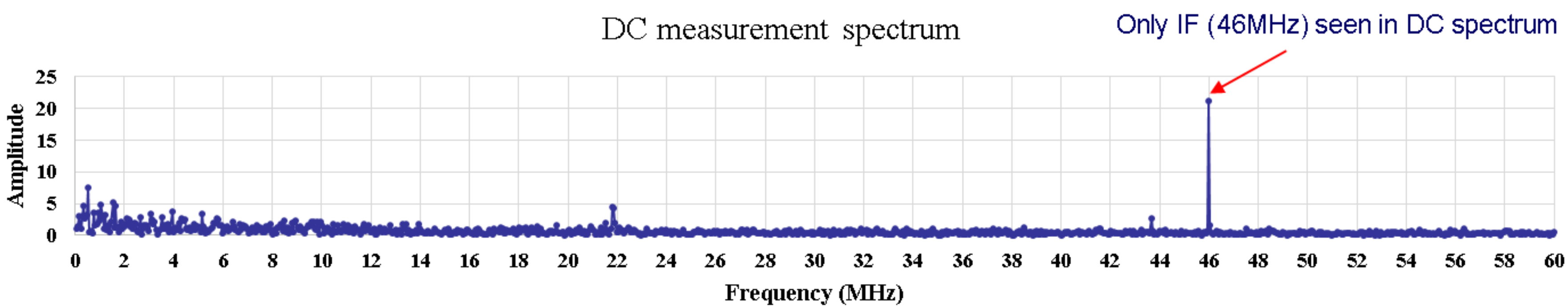
- <20 milli-degrees within a single pulse achieved
- Inter-pulse drift ~ 20 milli-degrees – phase shifter can be used to remove this
- DC and MT measurements are calibrated using the down converted phase.
- DC has less noise but its usefulness depends on amplitude correction



IF problems - Spectrums







IF problems - solutions

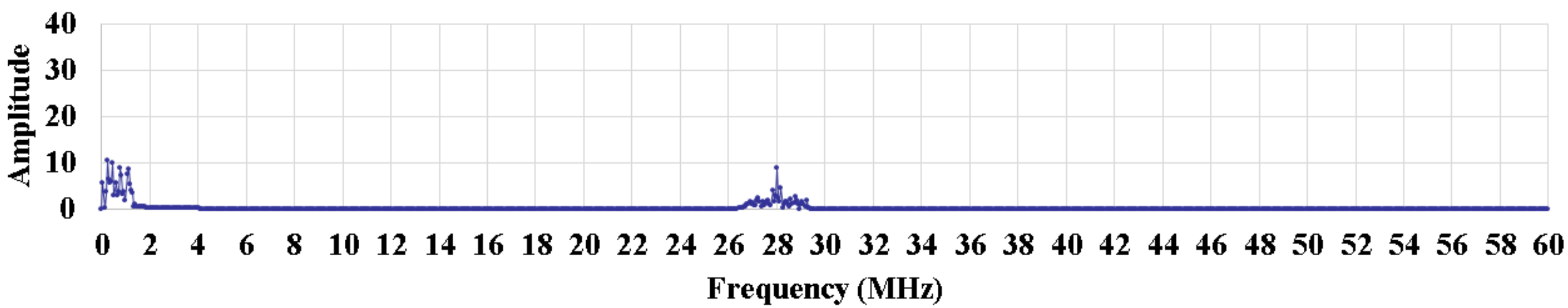
100MHz filters on IF

50MHz filter on DC

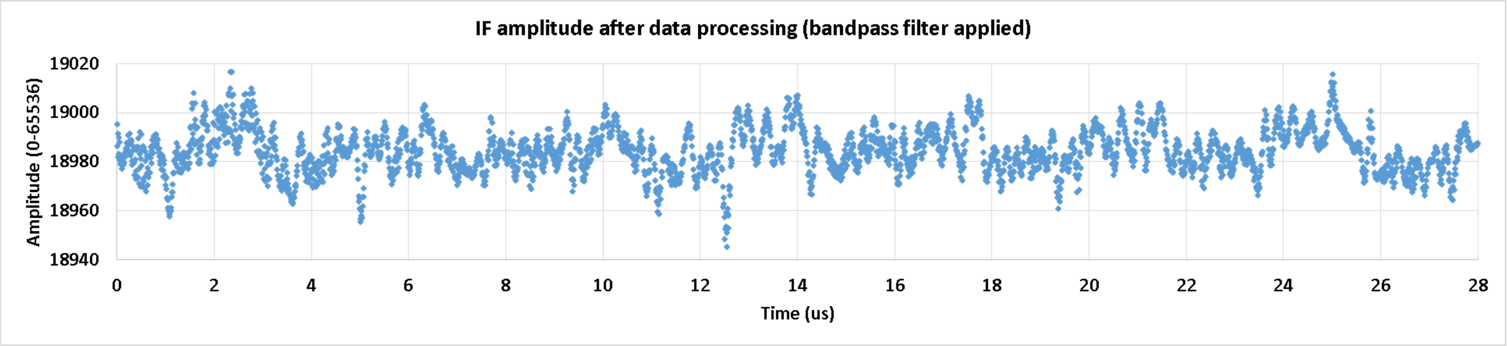
Unwanted frequencies generated by mixing between the harmonics of the IF frequency and the 120MHz clock. Other harmonics not present on DC as 50MHz filter is better than others.
IF frequency in DC removed with notch filter.

120 - (2x46) = 28MHz
120 - (3x46) = -18MHz
240 – (4x46) = 56MHz

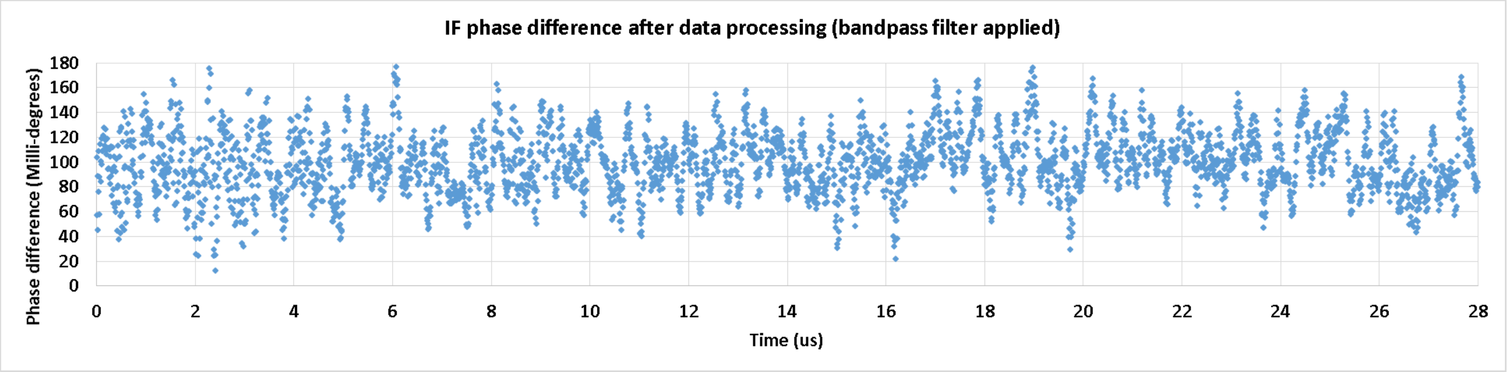
Calculated Phase spectrum after bandpass filter



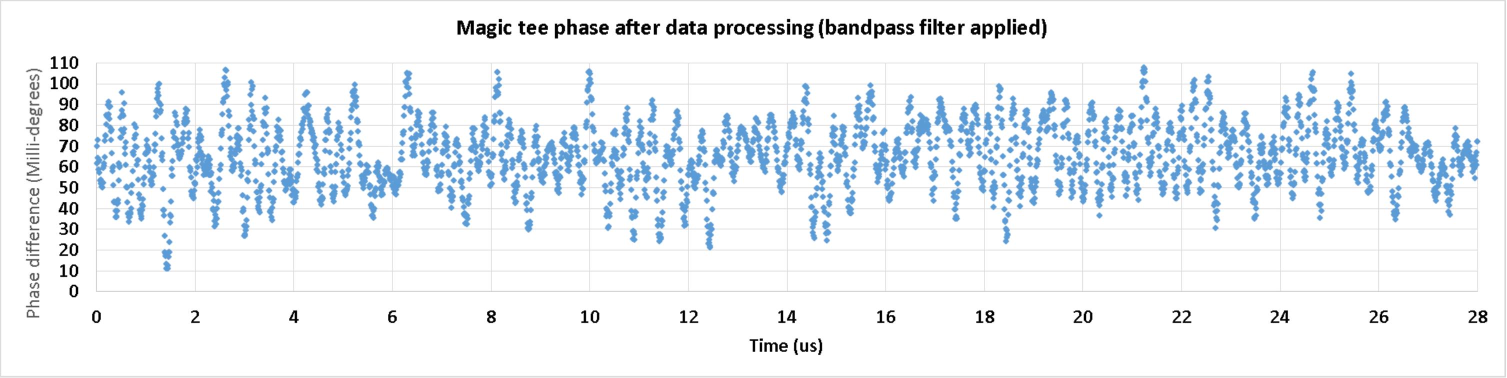
IF problems + solution



Noise spread ~ 40



Measured phase error ~ 140 milli-degrees

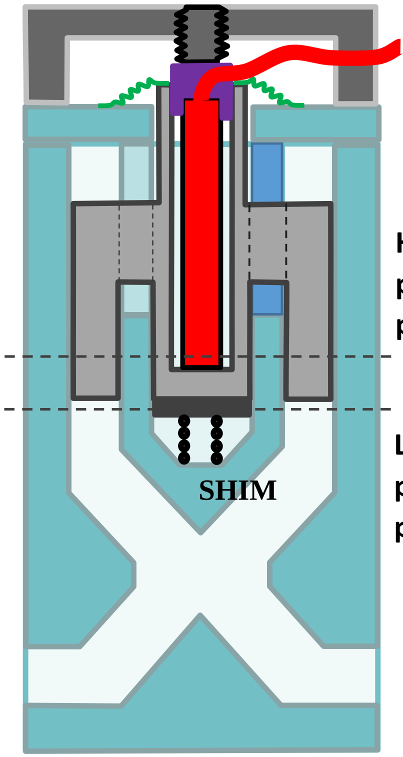


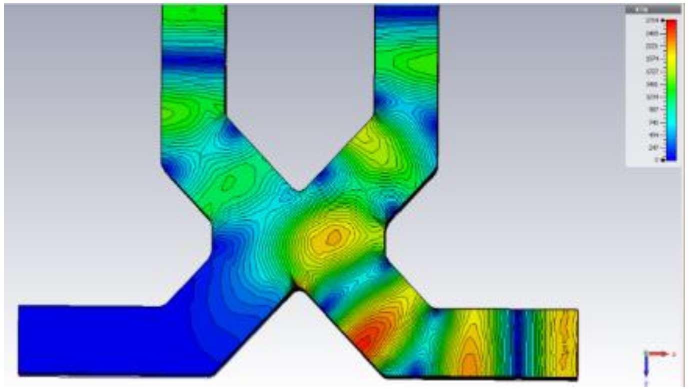
Measured phase error ~ 100 milli-degrees

Phase Shifter Requirement and Design

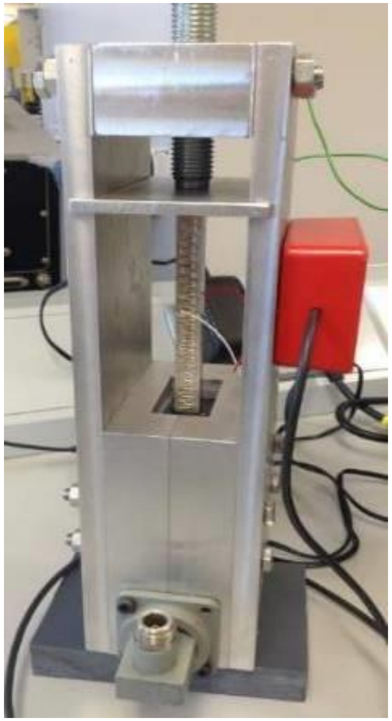
Phase shifter must:

- Work in high power conditions ~20 MW
- Give at least 4 degrees of fine tuning and half a wavelength of coarse tuning
- Have fast response times – 2 degrees of phase shift in 20ms and 0.1 degrees in 4ms (time between pulses is 20ms)
- Suitable for automation and integration into a control loop



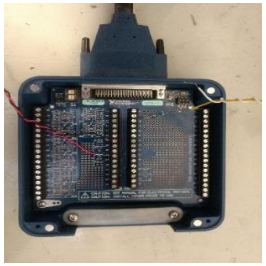


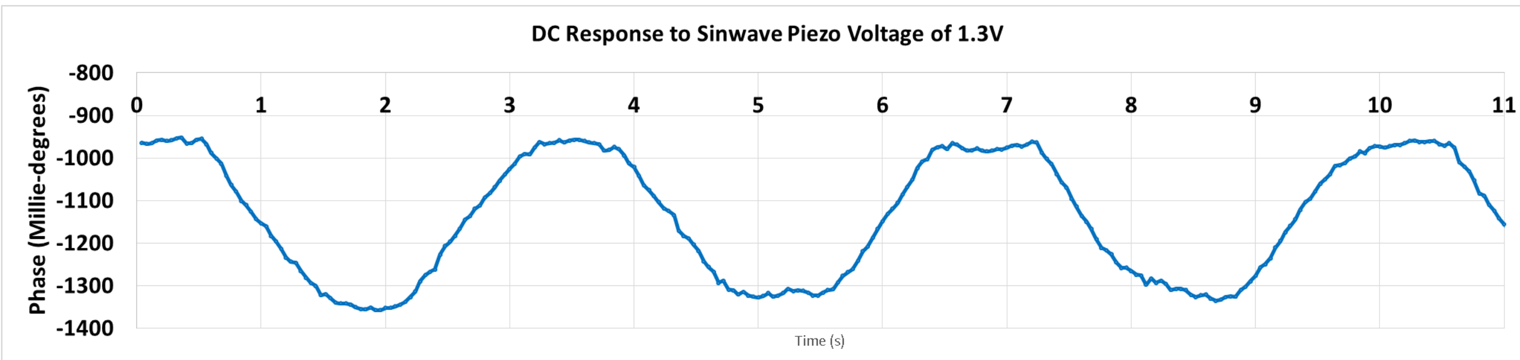
3dB Hybrid design – adapted from Alexej Grudiev
CLIC – Note – 1067

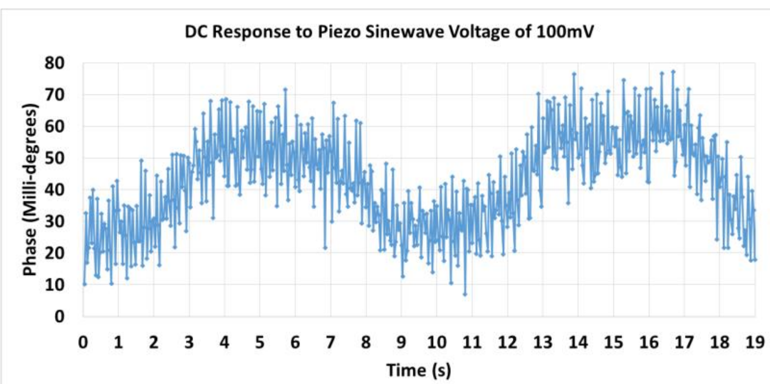


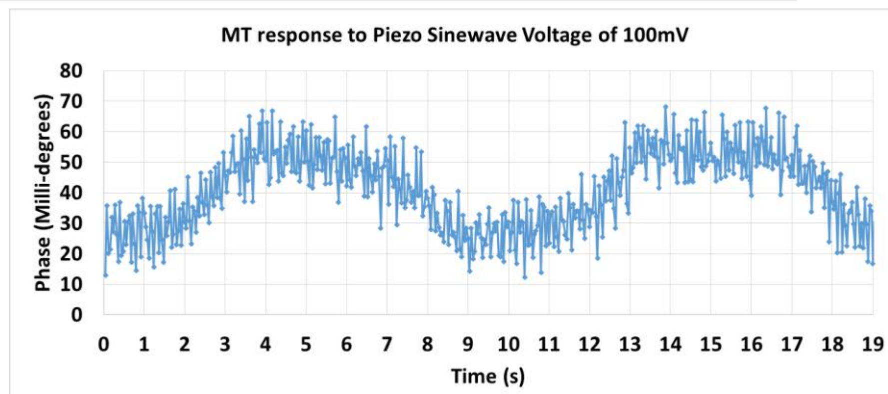
Prototype high power phase shifter built at Lancaster university, being used for current testing

Prototype Phase Shifter Performance

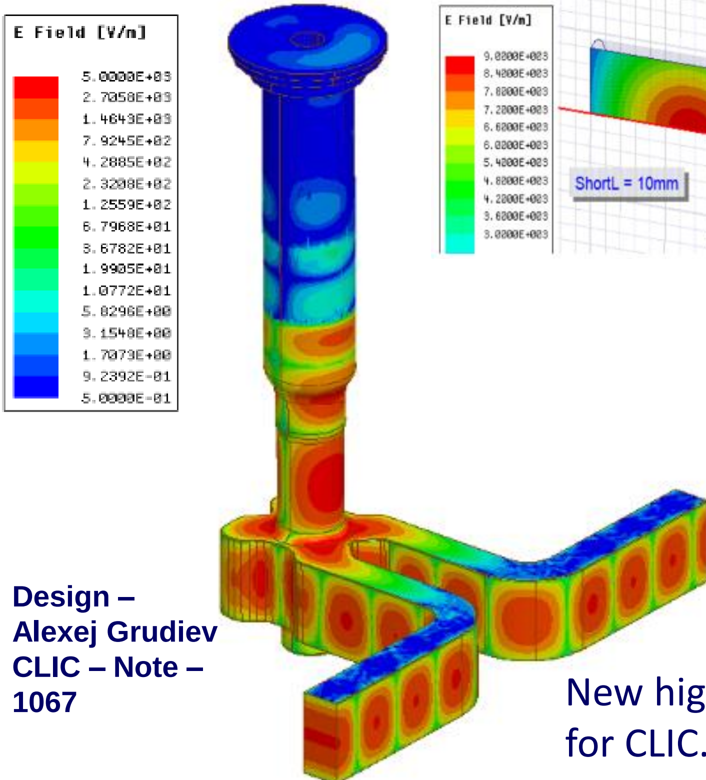


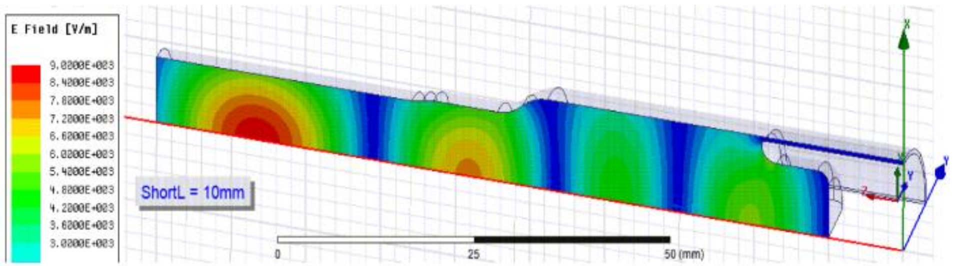


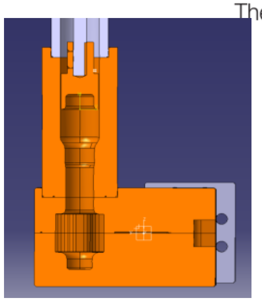




Lasted Phase Shifter Design

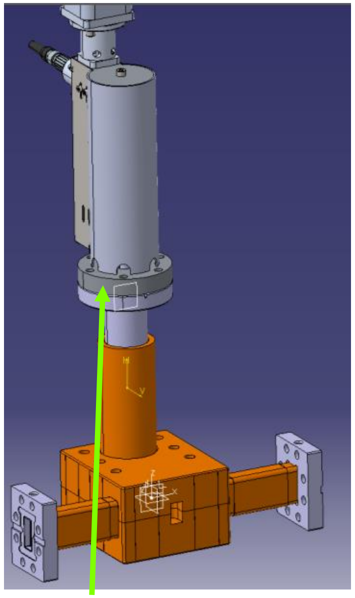






Converts waveguide TE10 mode to two polarisations of the TE11 circular waveguide mode.

Design – Alexej Grudiev CLIC – Note – 1067

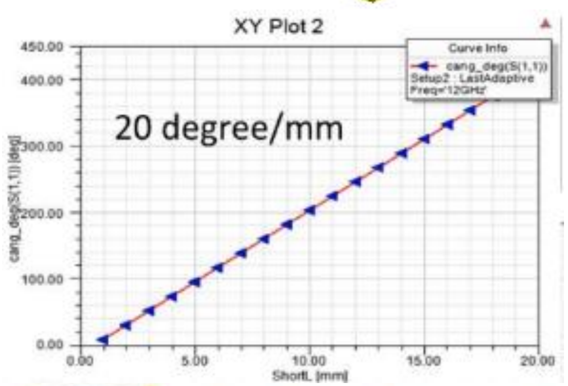


Flange allows for 2 attachments – motor for slow movements and piezo actuator for fast response

New high power phase shifter developed at CERN for CLIC. Design allows for integration of a stepper motor and piezo actuator giving solutions for the fast and slow phase shifters required.

Provides 20 degrees per mm, giving a piezo range of 6 degrees, enough for expected thermal expansion.

Drawings are finished and manufacturing will begin soon.



Achievements

- A PCB for mixing RF signals to d.c. and simultaneously mixing to an IF frequency has been developed. A key feature of the board is the management of path lengths to cancel reflections.
- An X-band waveguide interferometer has been set up with Piezo-activated phase shifters to control arm lengths.
- A National Instruments PXI data acquisition and control system has been set up to measure the phase difference and amplitude of signals returning on the interferometer arms.
- Measurement of phase differences at the resolution of 10 milli-degrees for 30 micro second pulses X-band has been demonstrated.
- Drawings for high power phase shifter completed – will be manufactured soon

Acknowledgements

This work was funded by

EUCARD grant 312453,

CERN and STFC as part of Cockcroft Institute Research Programme.

We acknowledge technical help and support from

Ben Woolley, Walter Wuensch, Alexei Grudiev, Igor Syratchev, Graeme Burt, Stephane Ray and Shokrollah Karimian.

Thanks for listening!