

# CLIC Crab Synchronisation

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**Eucard2 WP12 Annual Meeting**

**14<sup>th</sup> March 2017**

## CLIC requirement

- CLIC Crab cavity synchronization requirements - background
- 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

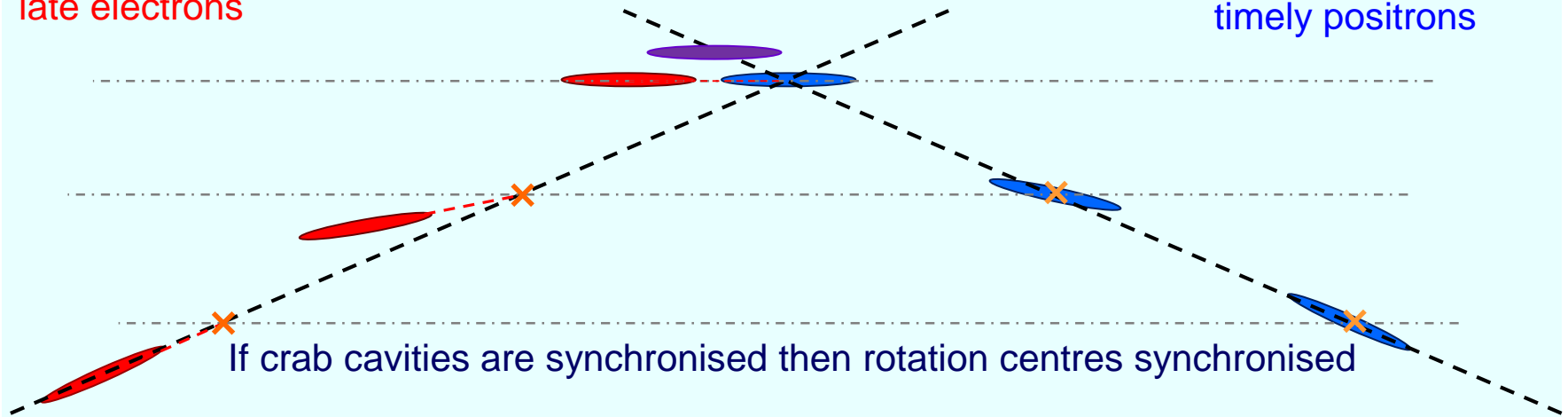
- Requirement and design
- Actuation
- Performance

## Achievements

collision point has small displacement

late electrons

timely positrons



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

**Cavity to Cavity Phase synchronisation requirement (excluding bunch attraction)**

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

Target max. luminosity loss fraction S	f (GHz)	$\sigma_x$ (nm)	$\theta_c$ (rads)	$\phi_{\text{rms}}$ (deg)	$\Delta t$ (fs)	Pulse Length ( $\mu\text{s}$ )
0.98	12.0	45	0.020	0.0188	4.4	0.156

## 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.

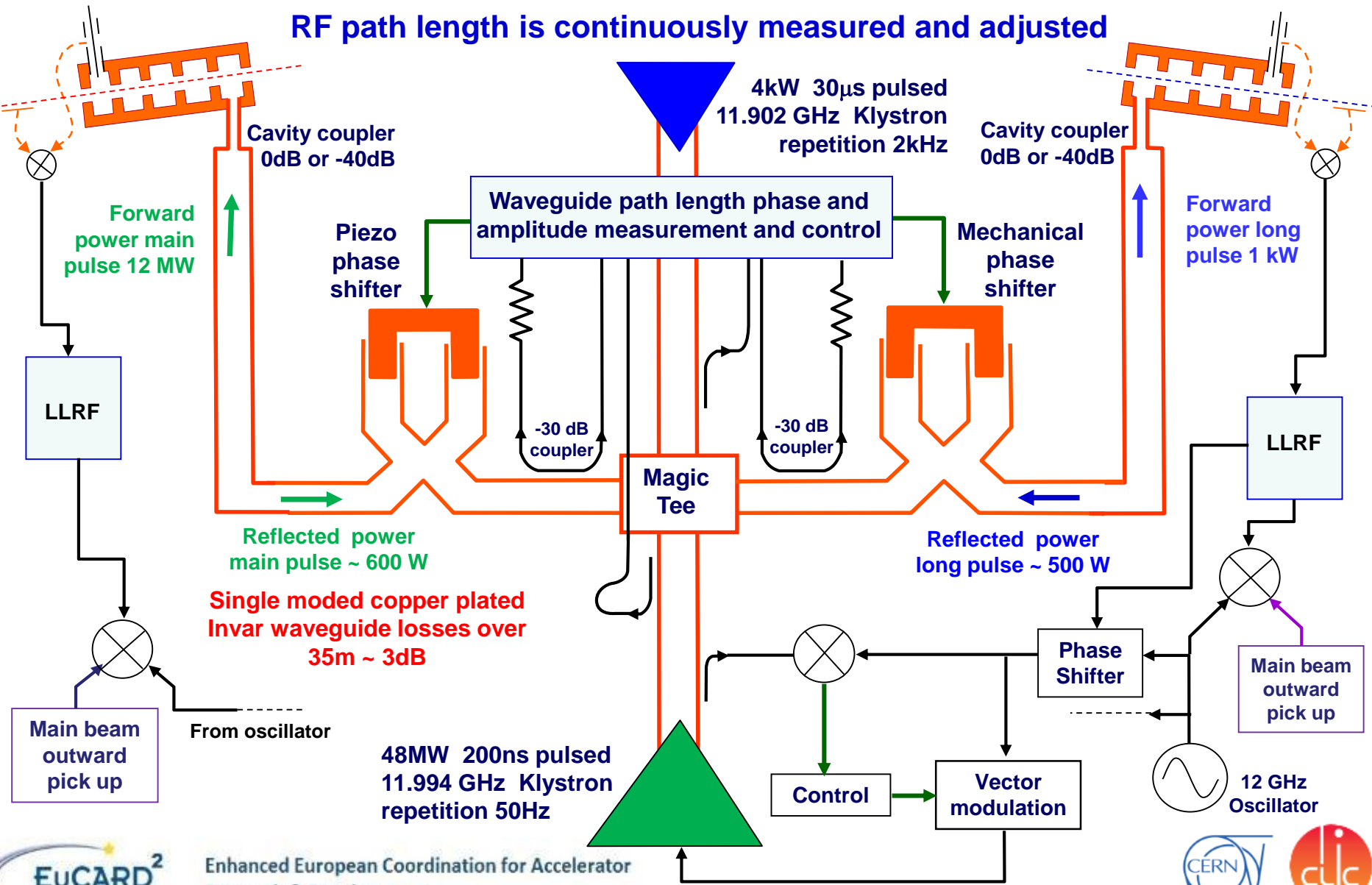
Femto-second level stabilised optical distribution systems have been demonstrated (XFELs).

**BUT**

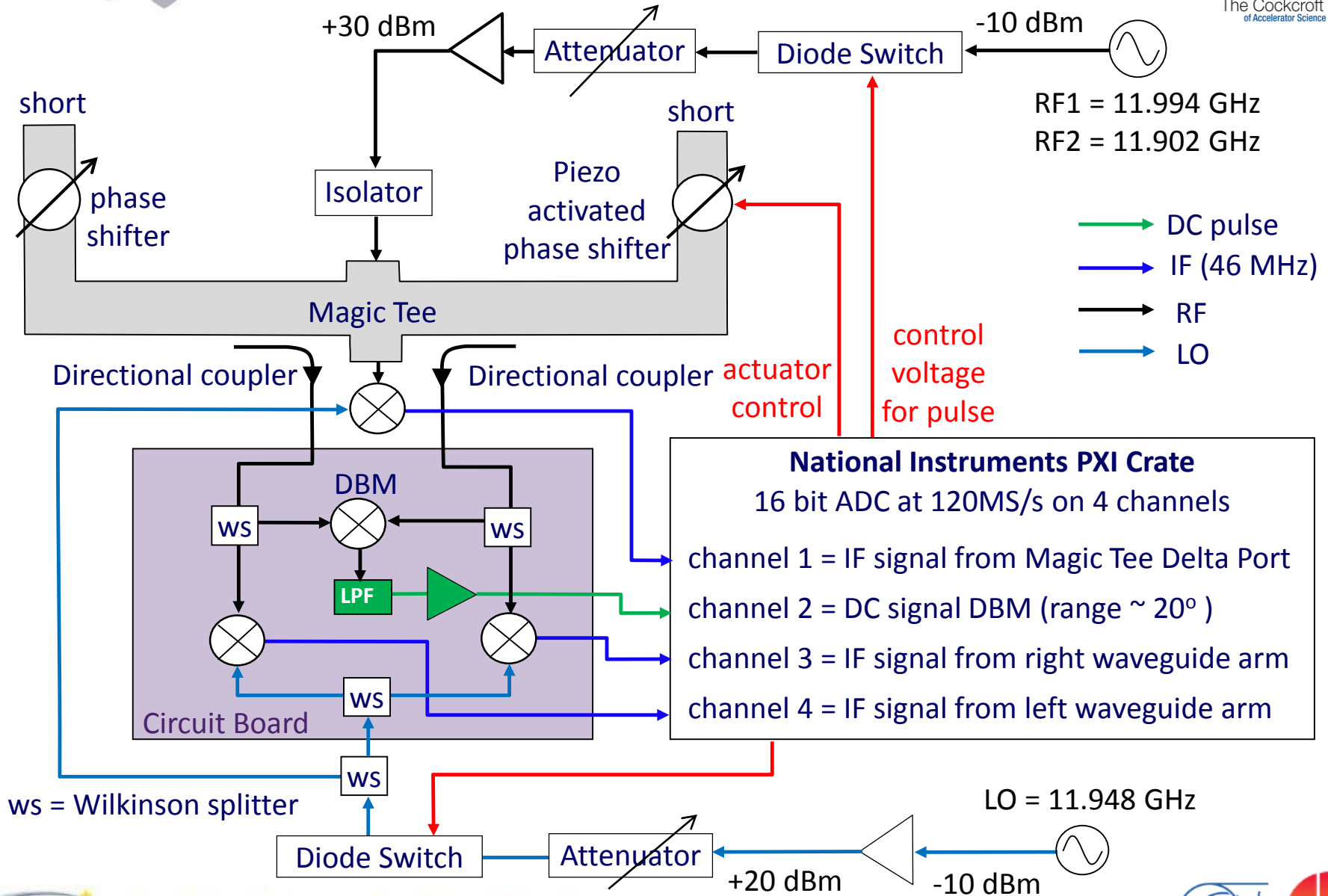
Requires klystron output with integrated phase jitter <4.4 fs.

# CLIC Synchronisation Proposal

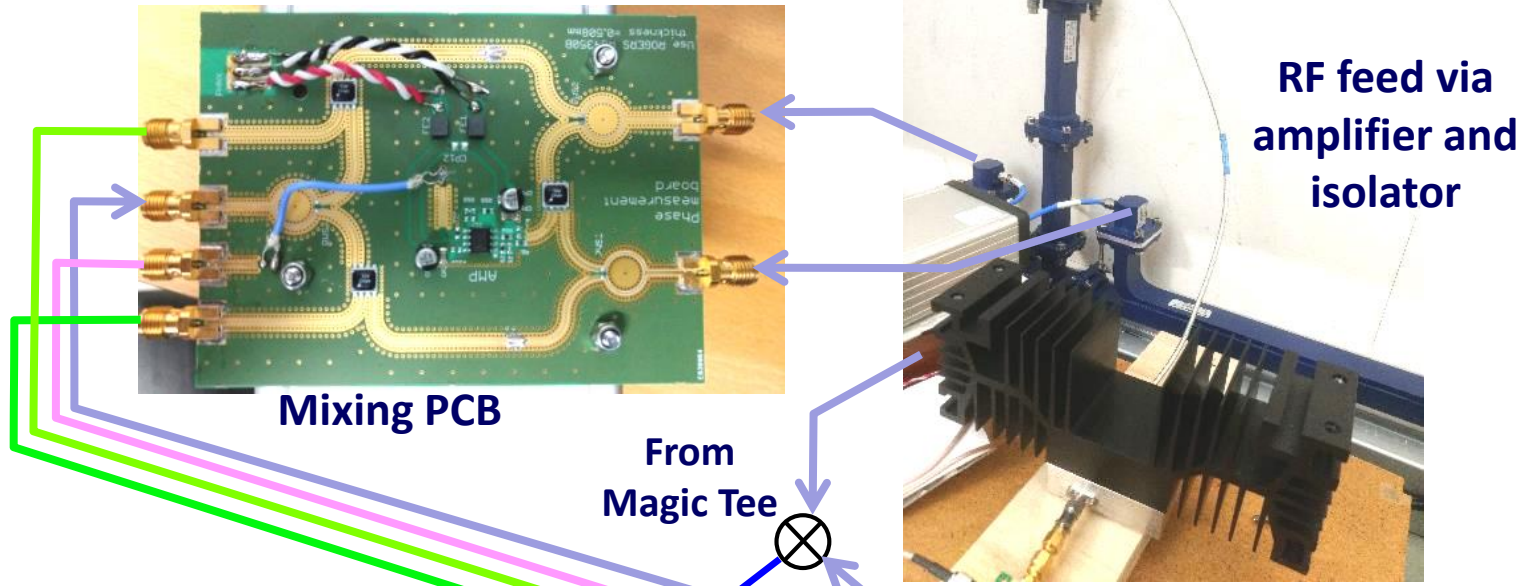
RF path length is continuously measured and adjusted



# Feasibility Measurement Scheme



# Electronics

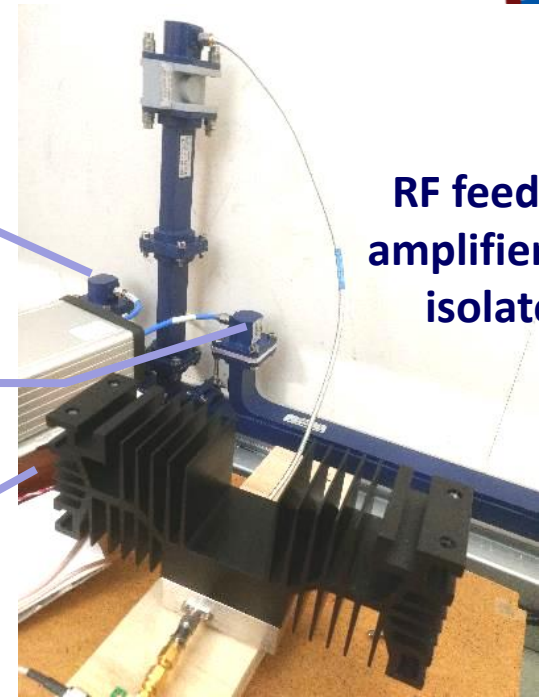


**NI PXI Spec.:**

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



**National Instruments PXI crate**



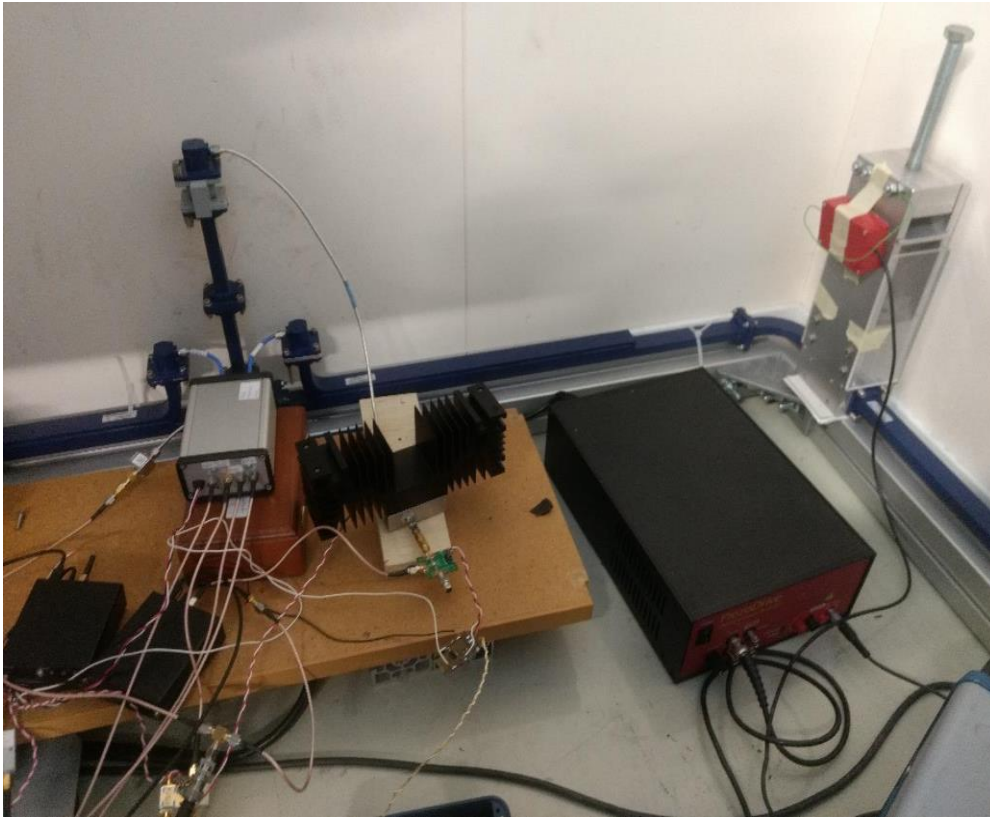
**RF feed via amplifier and isolator**



**Pin diode switch to pulse RF**



**Locked DI Instruments Oscillators (\$700)**

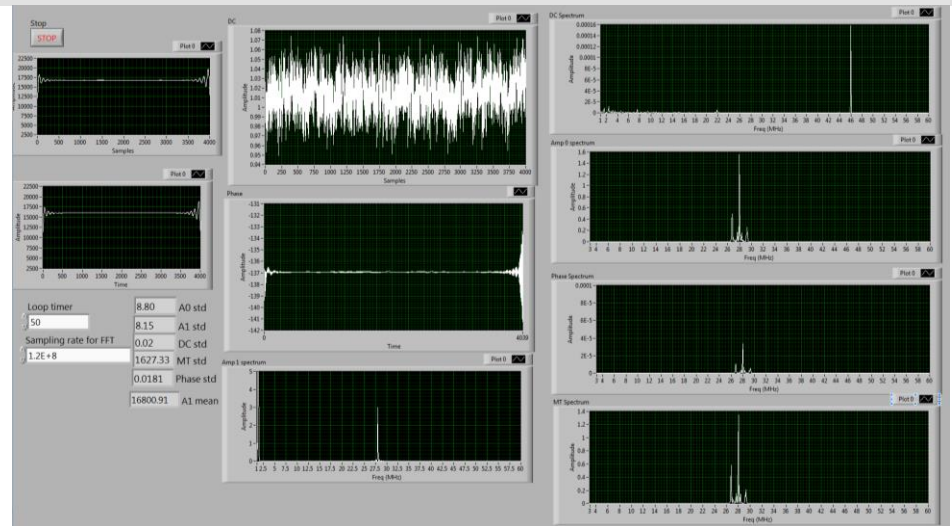
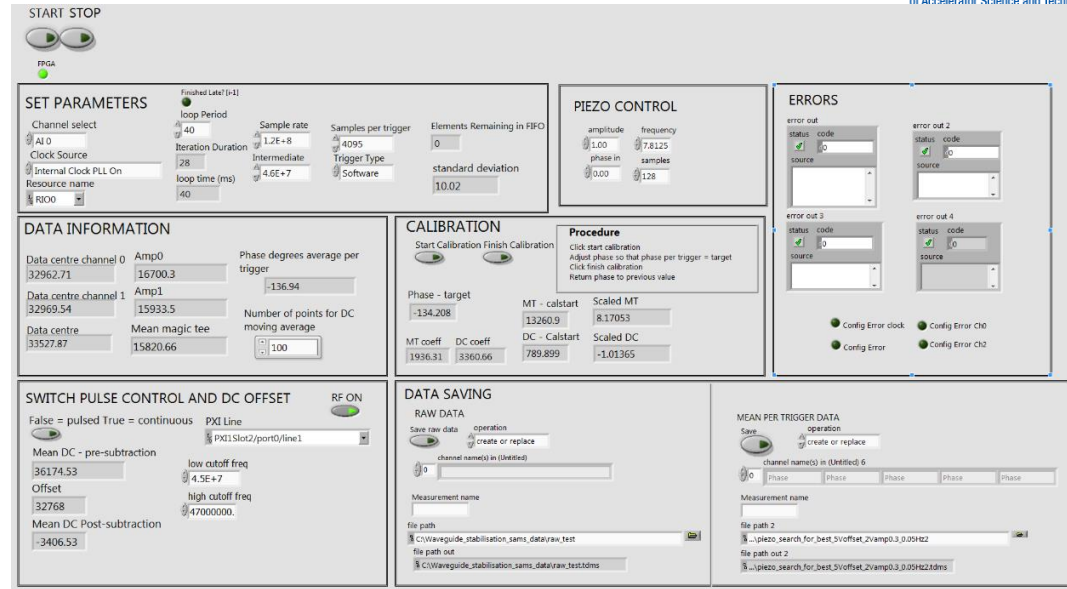


**Waveguide runs around edge of RF lab –  
phase shifters and attenuators on each arm**



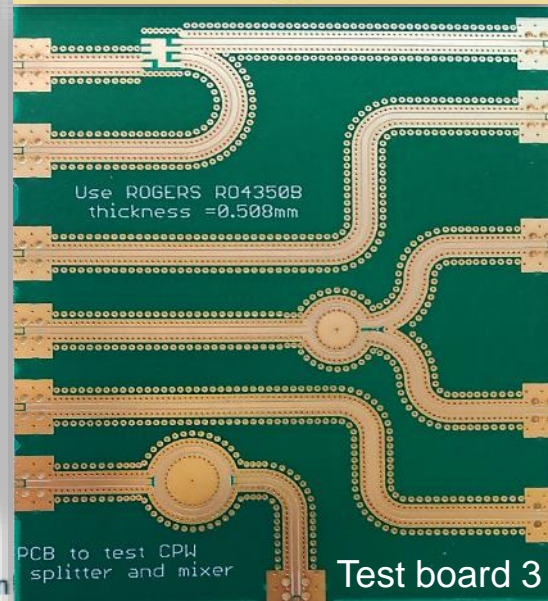
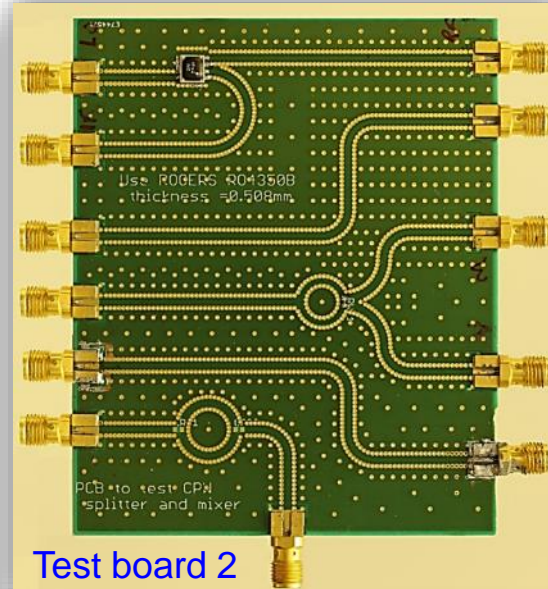
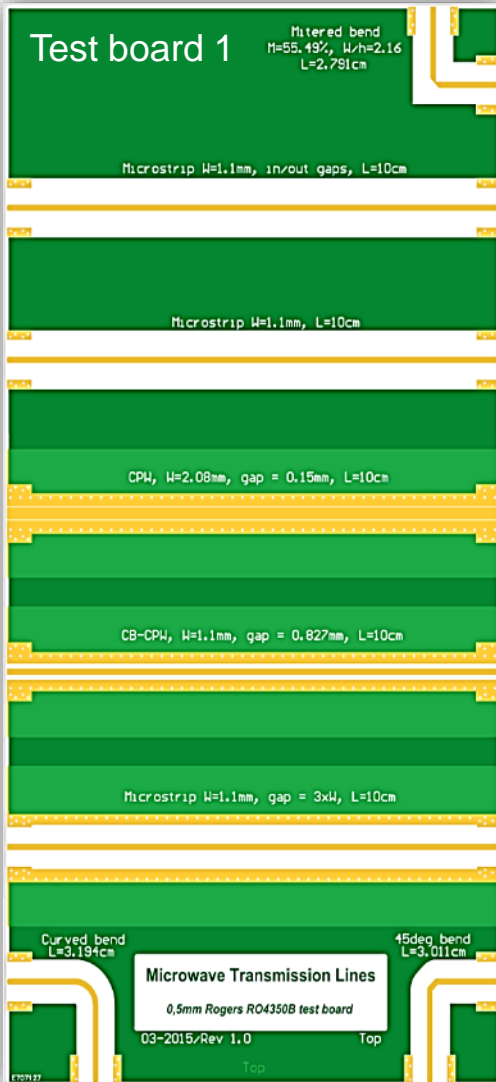
## LabVIEW used for acquisition

- 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



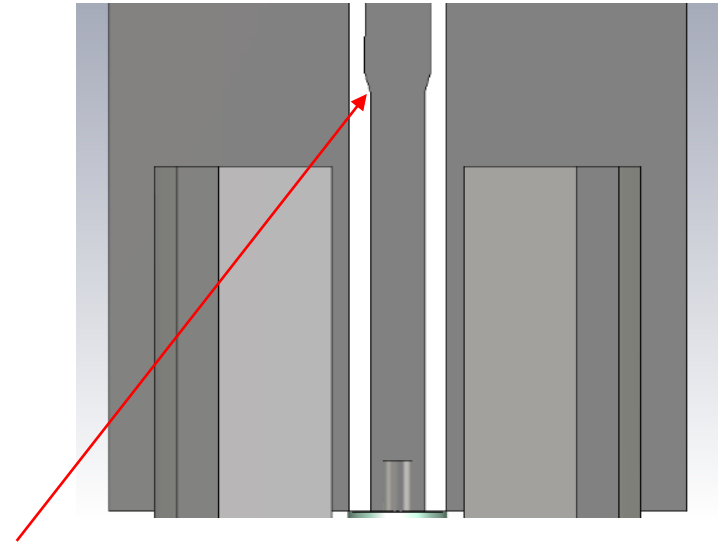
## NI PXI Spec.:

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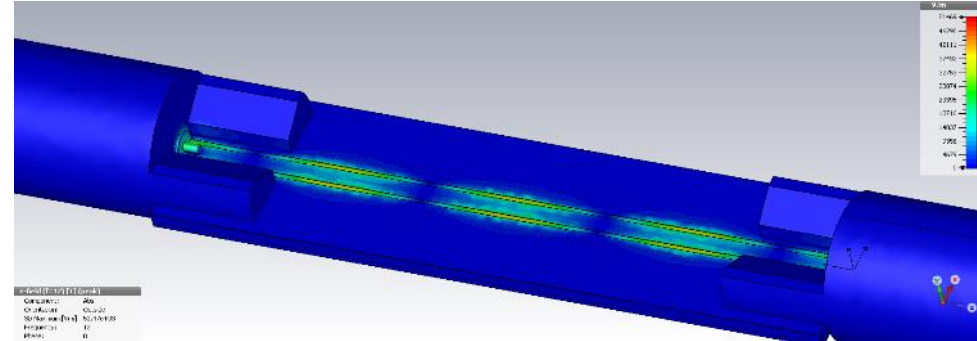
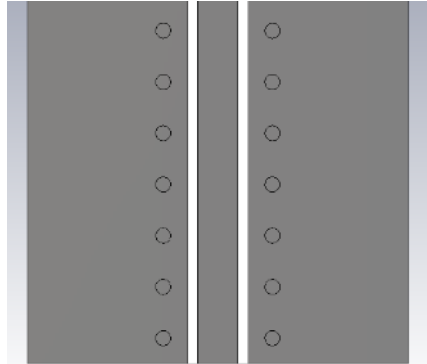
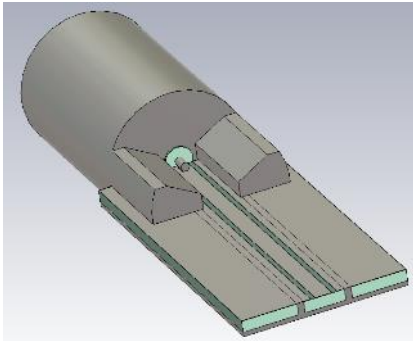


- Multiple **test boards** have been developed to achieve optimum performances at 10-12GHz.
- Test board 1 examined:
  - ❑ Choice of optimum transmission line (Microstrip, CPW, GCWP, Stripline, ...)
  - ❑ Impedance matching and transmission responses
  - ❑ SMA connector type, bends, etc.
  - ❑ And measured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

- 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

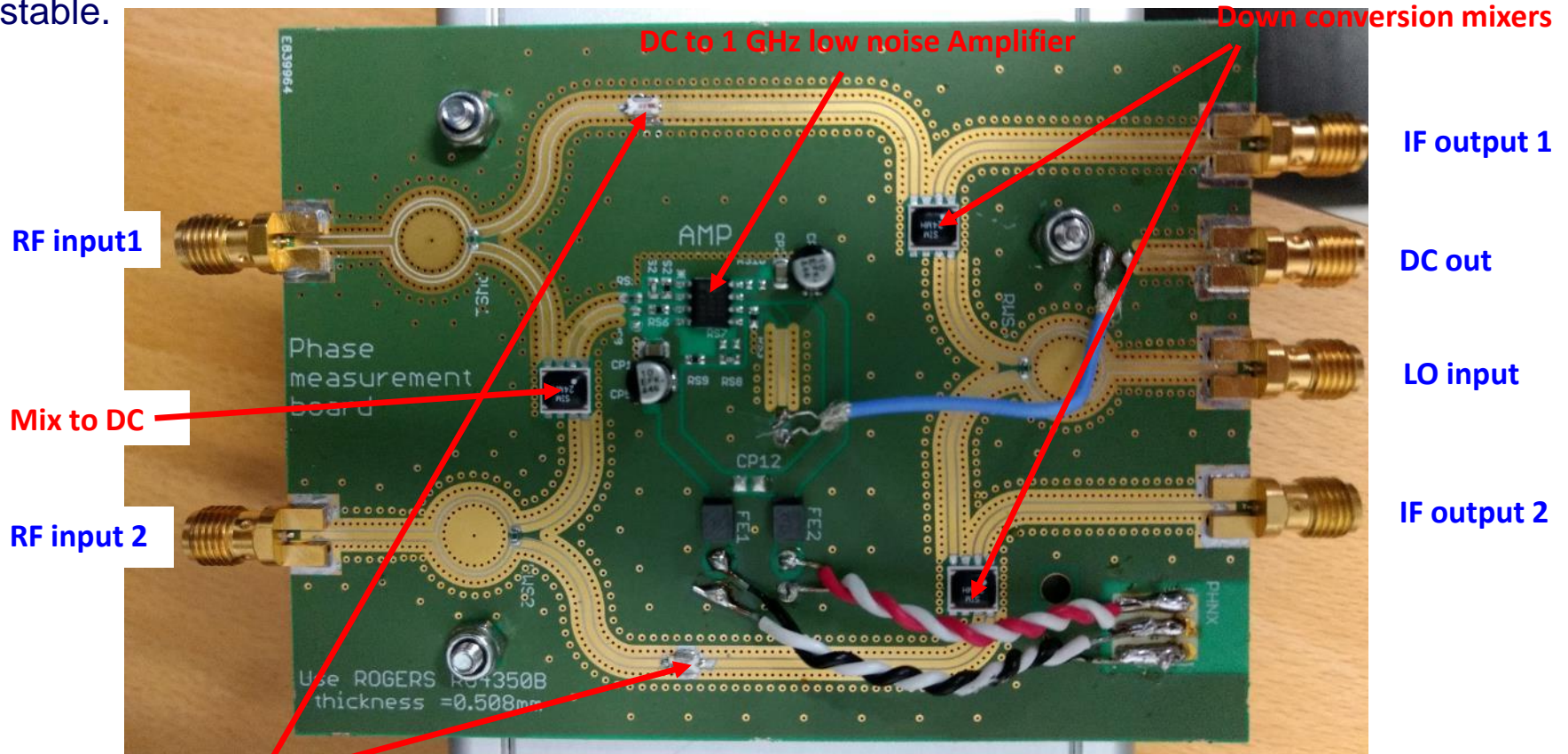


Track width taper at launch pad



# 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.

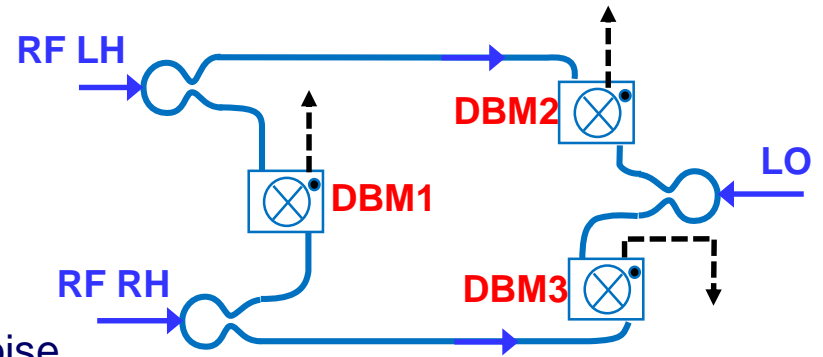


**IF filters**  
Added to improve  
isolation on DC mixer

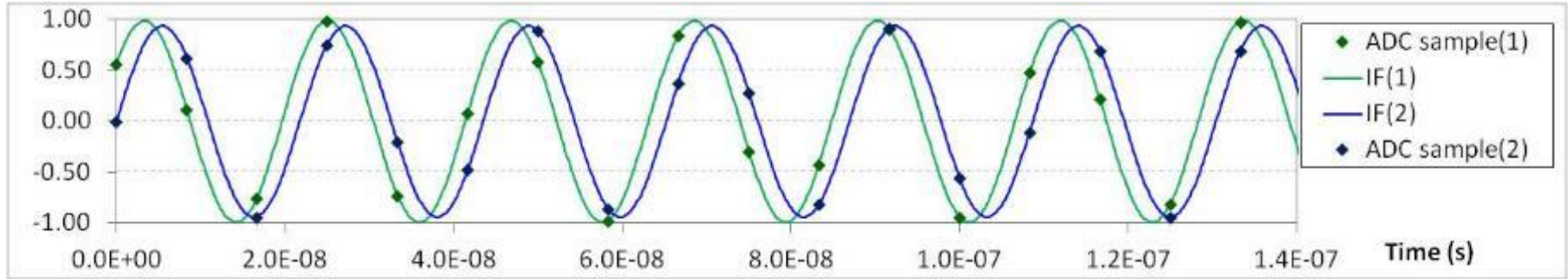
- Green Solder Resist removed from above CPW
- Tappers introduced to PCB plan for improved connector matching

**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  $360^\circ$  cannot be measured (PXI input limitation).
- Direct sampling of DBM2 and DBM3 allows:-
  - $360^\circ$  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



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

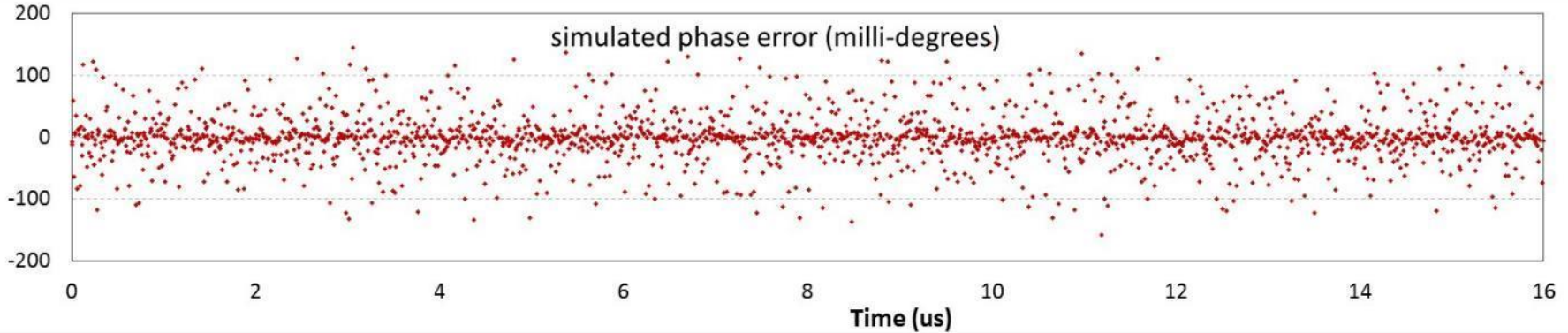


Deduce phase using

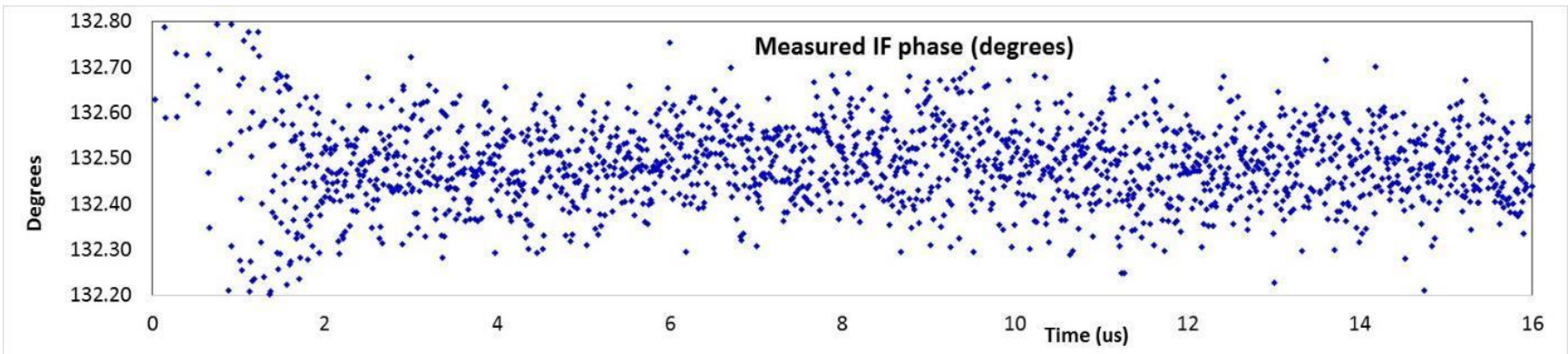
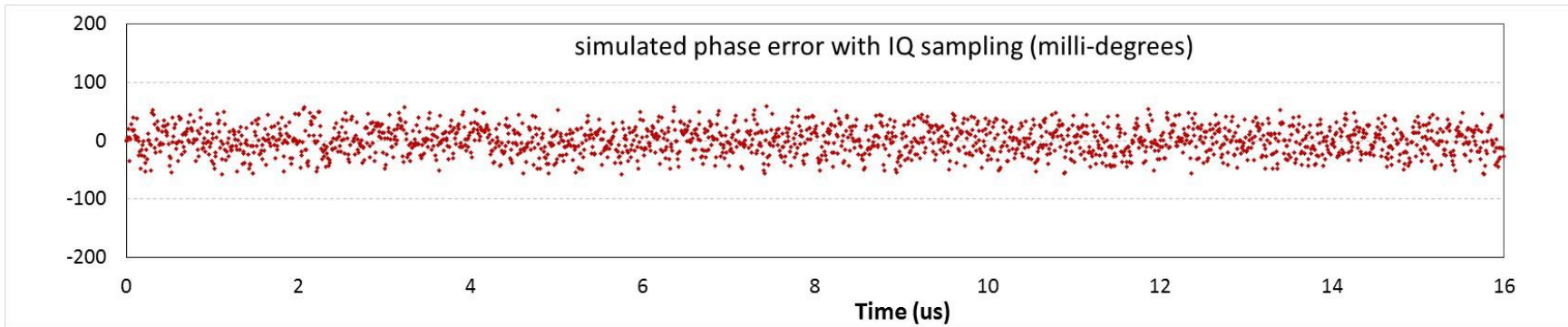
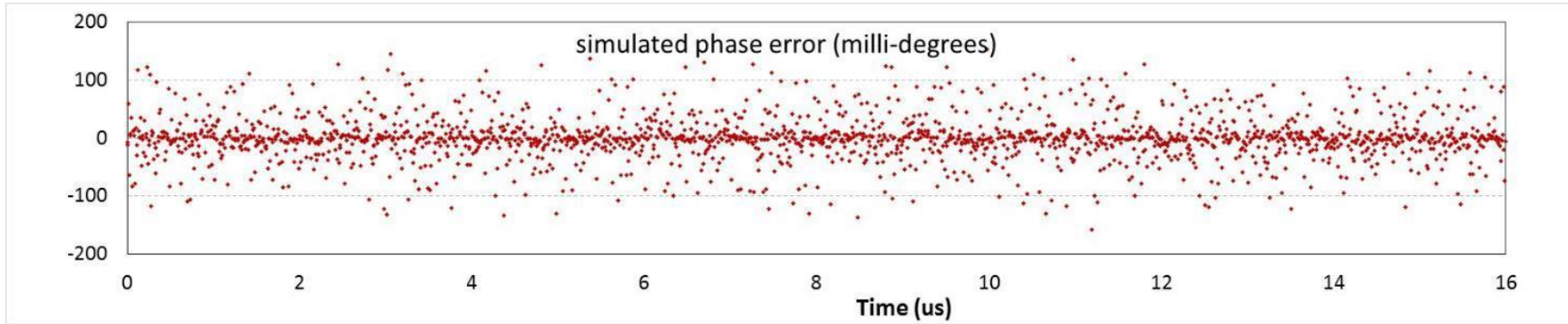
$$\phi = \tan^{-1}\left(\frac{y_1(n) - y_1(n+1)}{y_1(n) + y_1(n+1)} C\right) - \tan^{-1}\left(\frac{y_2(n) - y_2(n+1)}{y_2(n) + y_2(n+1)} C\right) \quad \text{where} \quad C = \cot\left(\pi \frac{f_{IF}}{f_{sample}}\right)$$

Simulated ADC errors (assumes noiseless input to the ADC)

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



# Expected versus Actual Performance for IF

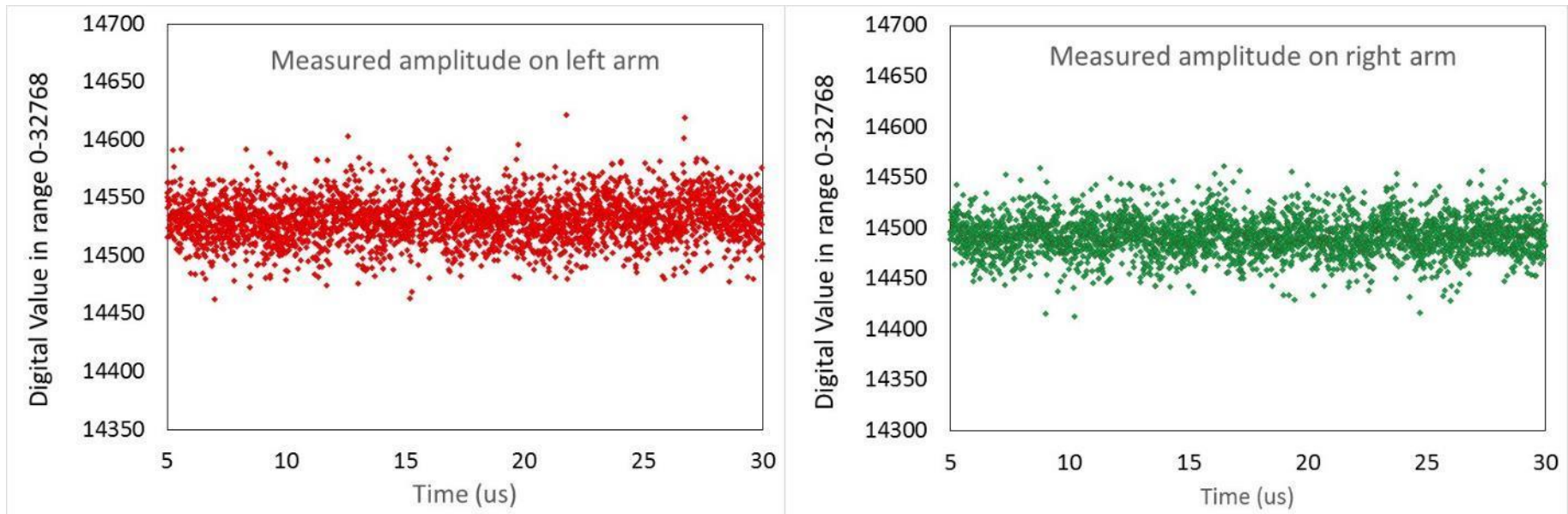


# Amplitude Determined from IF

Amplitude determined from adjacent sampled points  $y_0$  and  $y_1$  on IF waveform using

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

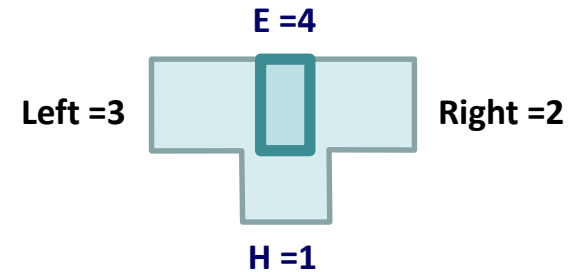
Originally notch filters are applied to the raw data to remove the IF frequency of 46 MHz and other spurious frequencies



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



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

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

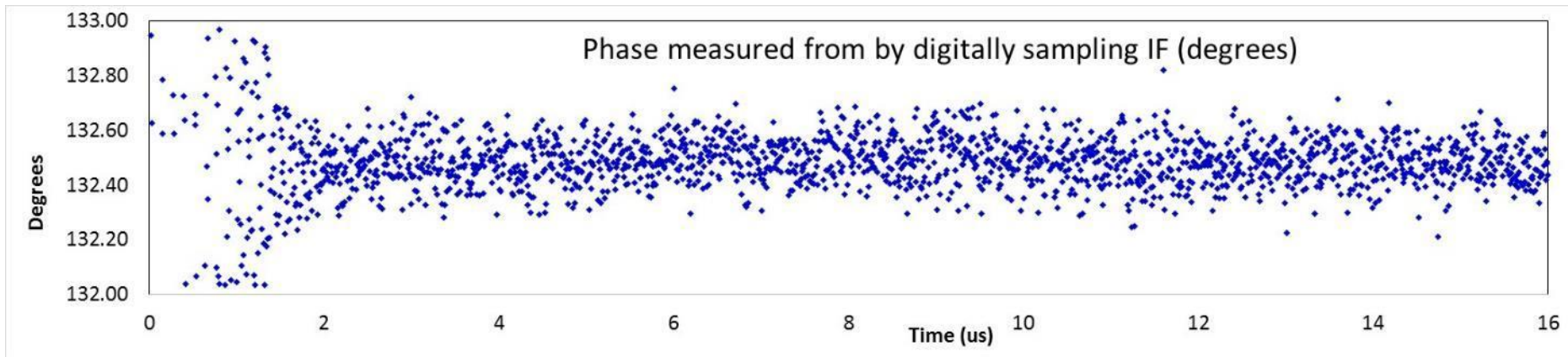
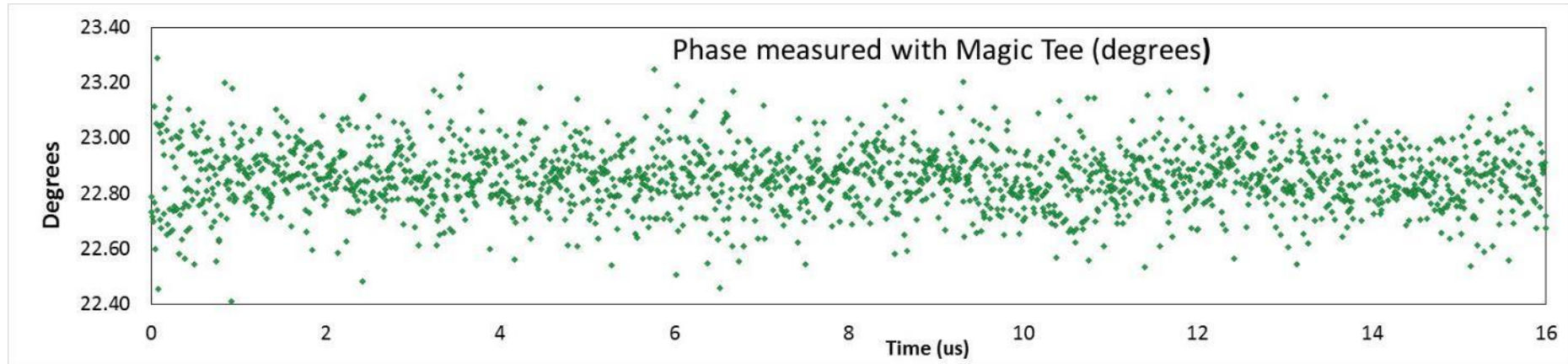
Measuring amplitude  $V_4$  from port 4 we have

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

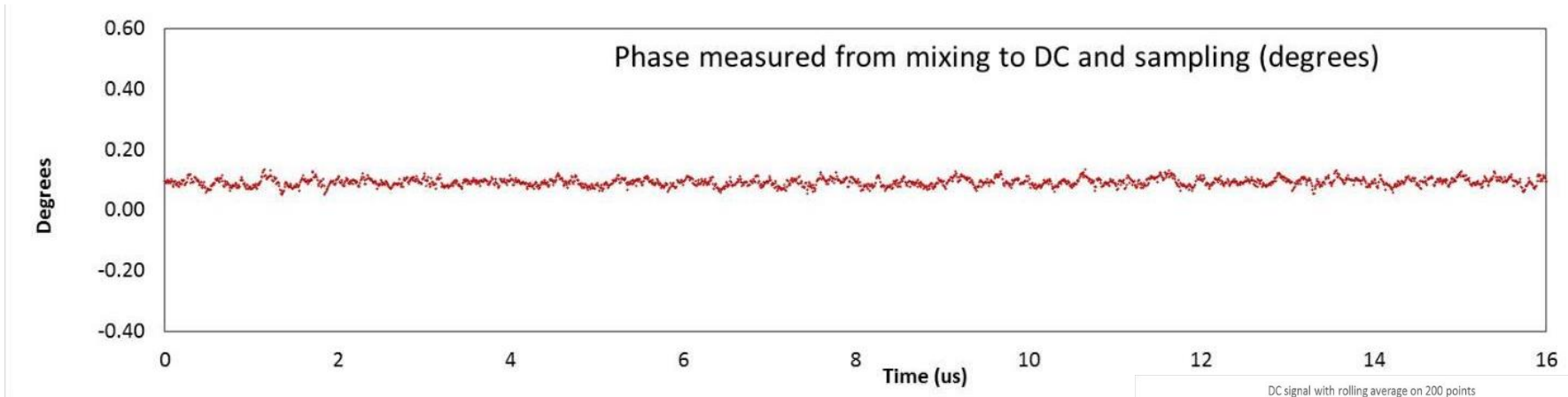
The phase difference between ports 2 and 3 depends on input amplitudes to the ports as well as output on port 4.

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

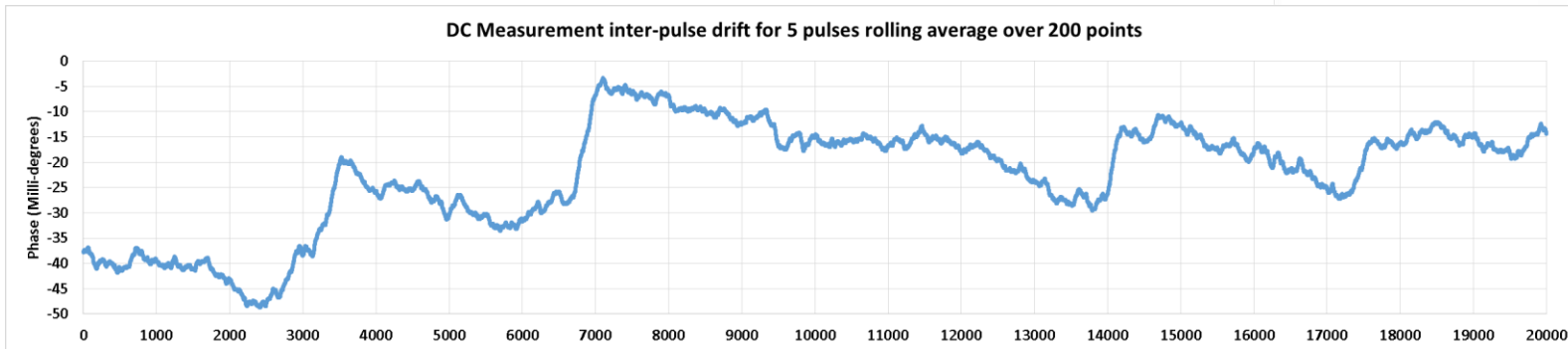
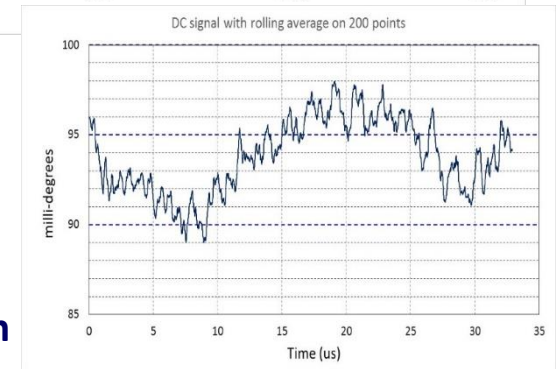
Vertical range is 1 degree for both graphs



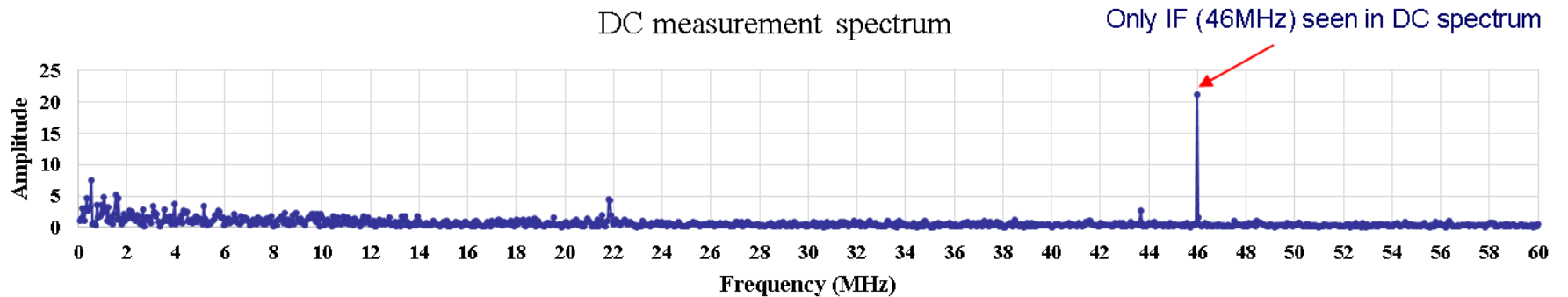
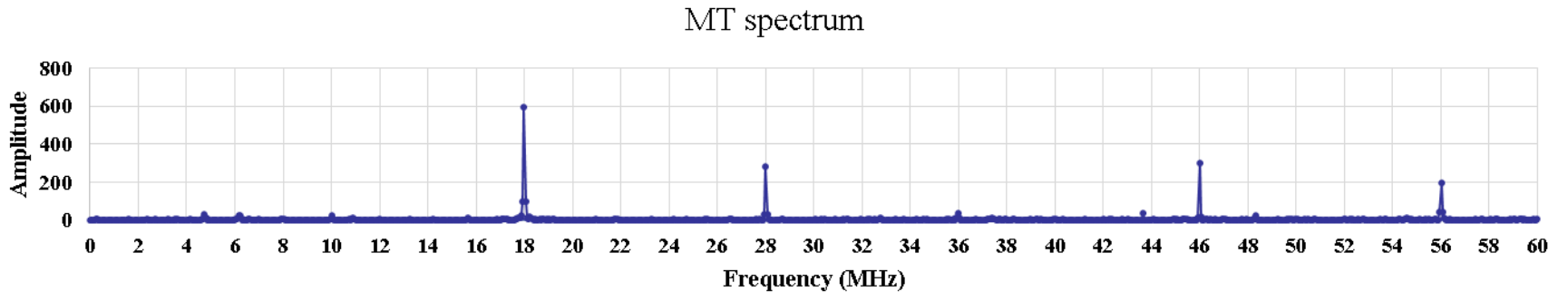
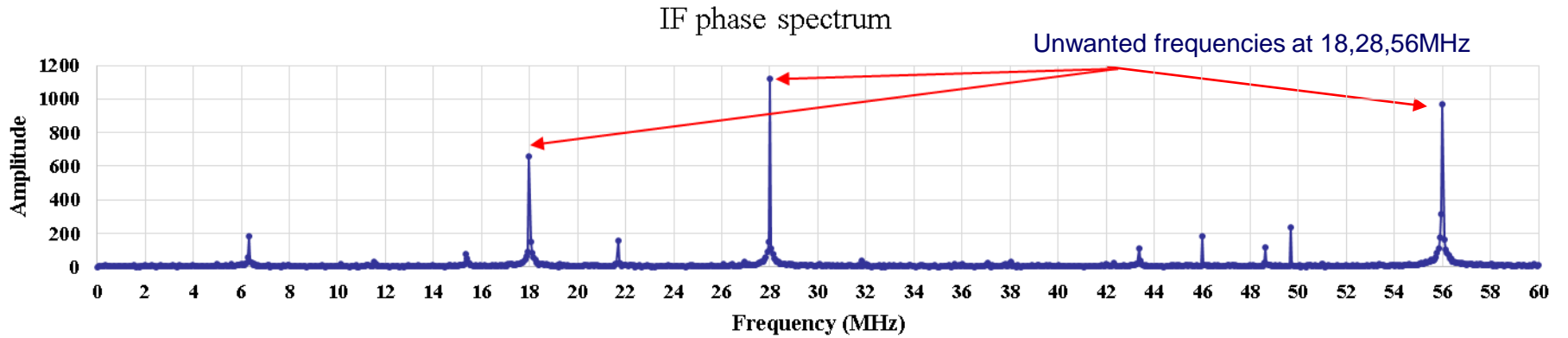
The Magic Tee measurements did not use the phase board and SIM24 MH+ mixer, this might explain the slightly high level of noise.



- <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

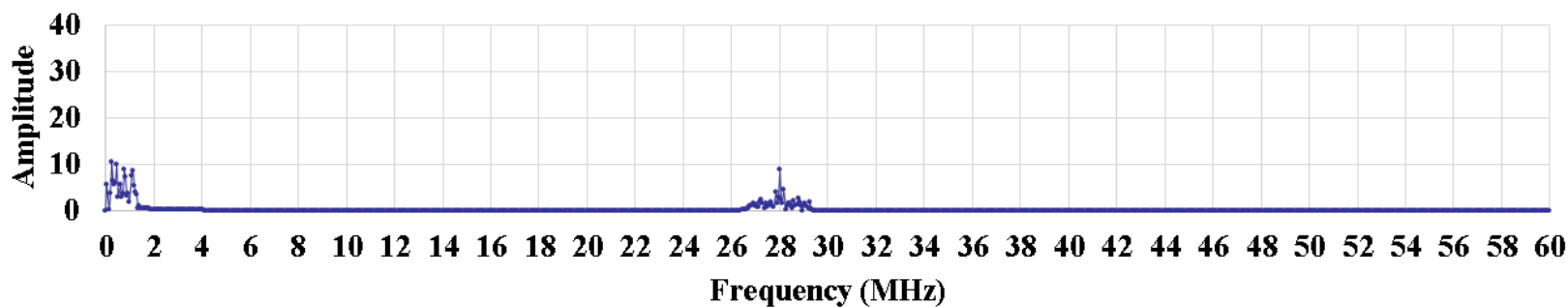
Unwanted frequencies generated by mixing between the harmonics of the IF frequency and the 120MHz clock. Other harmonics not present on DC as 50MHz filter is better than others. IF frequency in DC removed with notch filter.

$$120 - (2 \times 46) = 28\text{MHz}$$

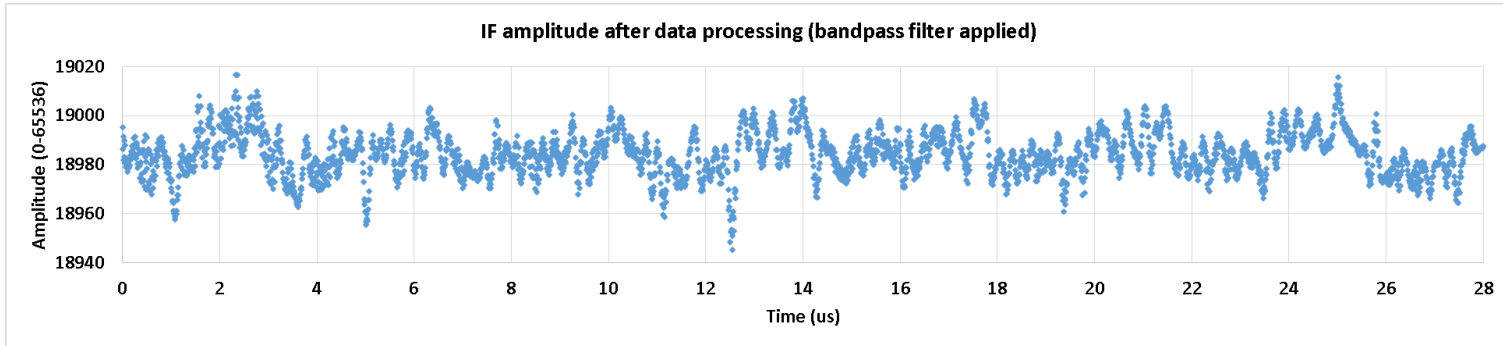
$$120 - (3 \times 46) = -18\text{MHz}$$

$$240 - (4 \times 46) = 56\text{MHz}$$

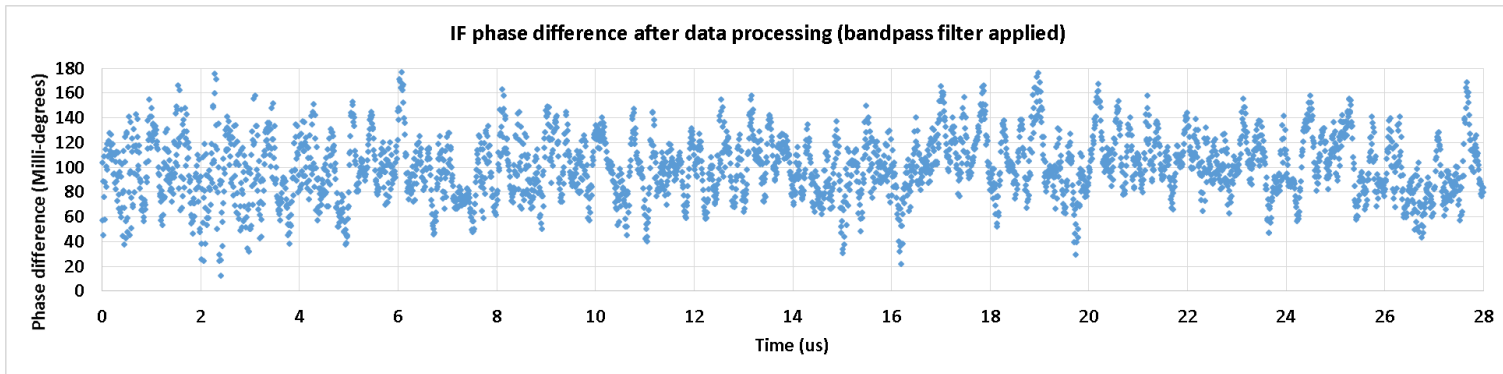
Calculated Phase spectrum after bandpass filter



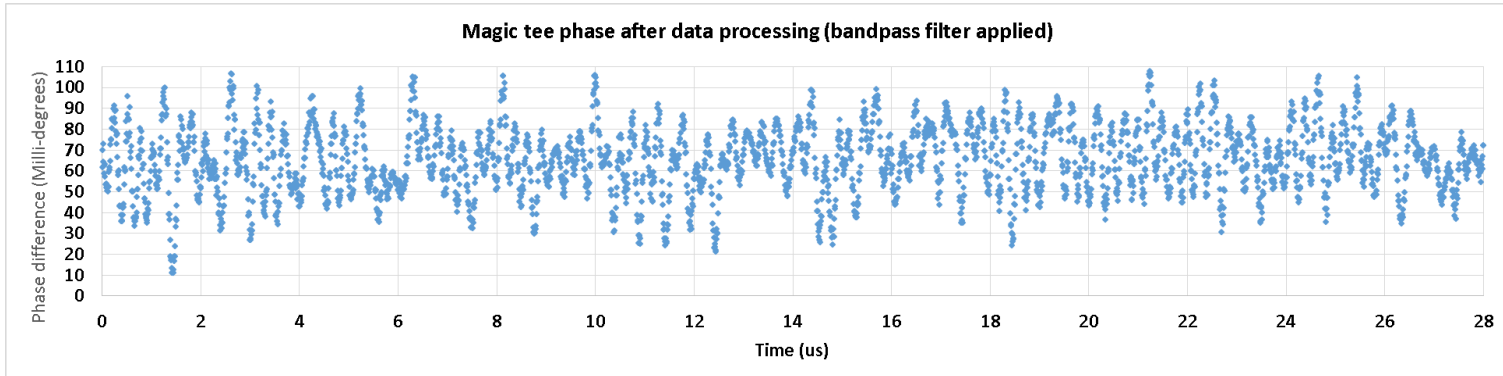
# IF problems + solution



Noise spread ~ 40



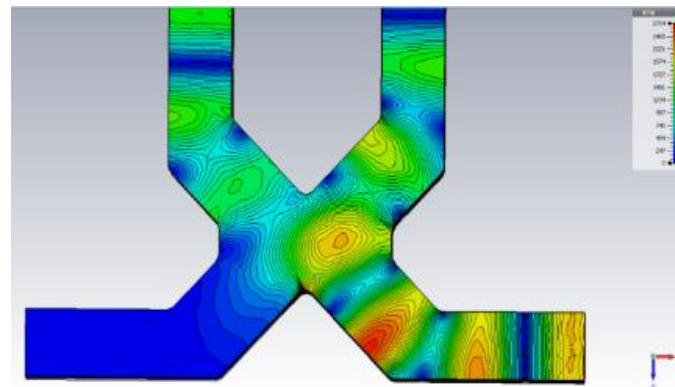
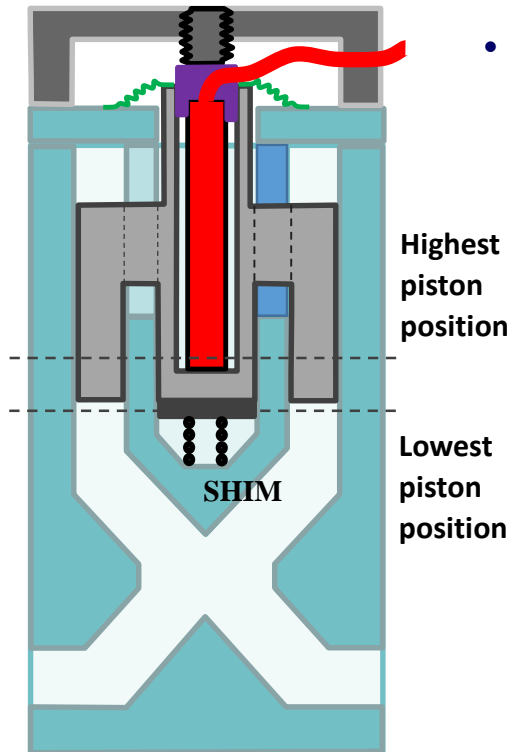
Measured phase error ~ 140 milli-degrees



Measured phase error ~ 100 milli-degrees

## Phase shifter 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

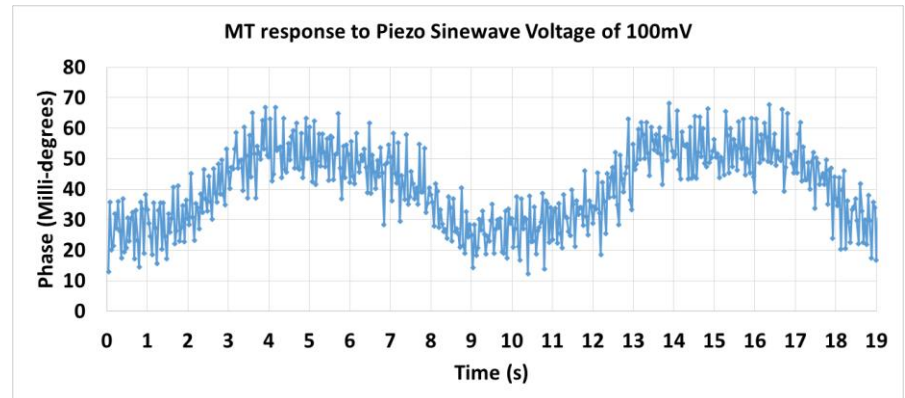
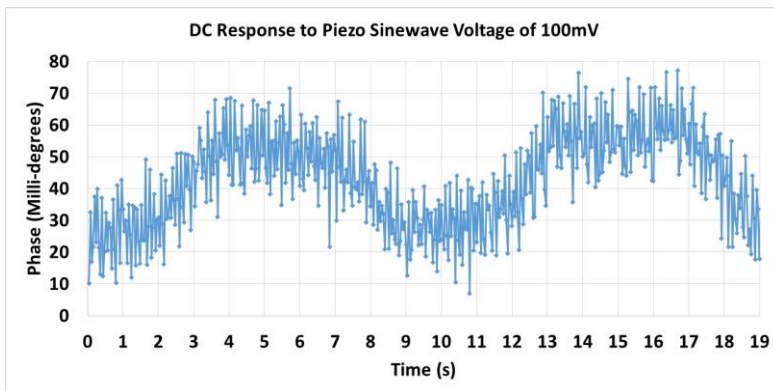
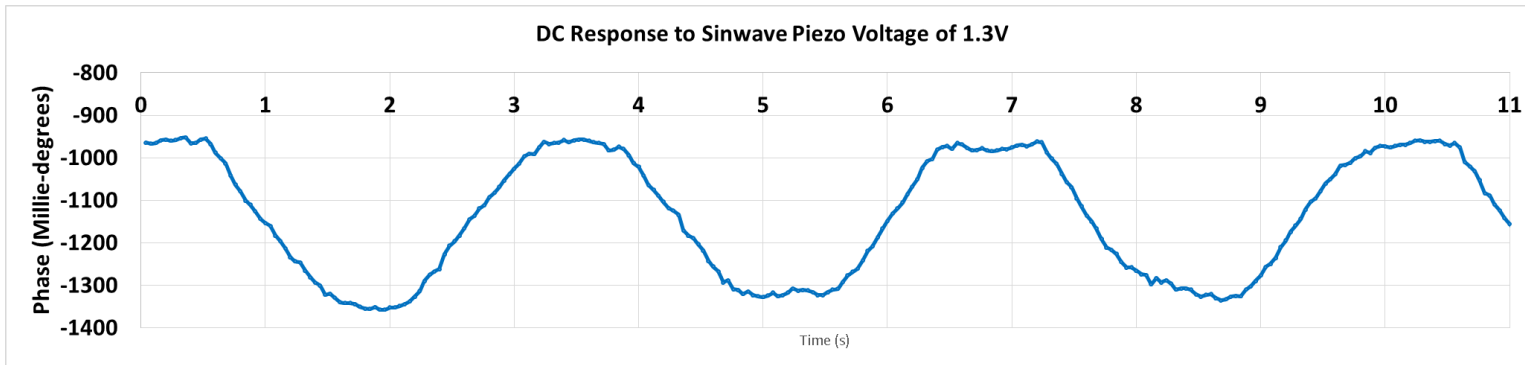
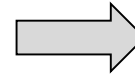
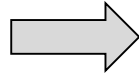
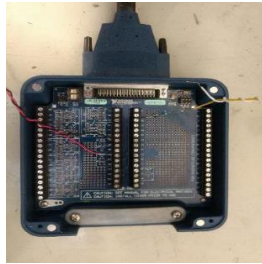


3dB Hybrid design – adapted from  
Alexej Grudiev  
CLIC – Note – 1067

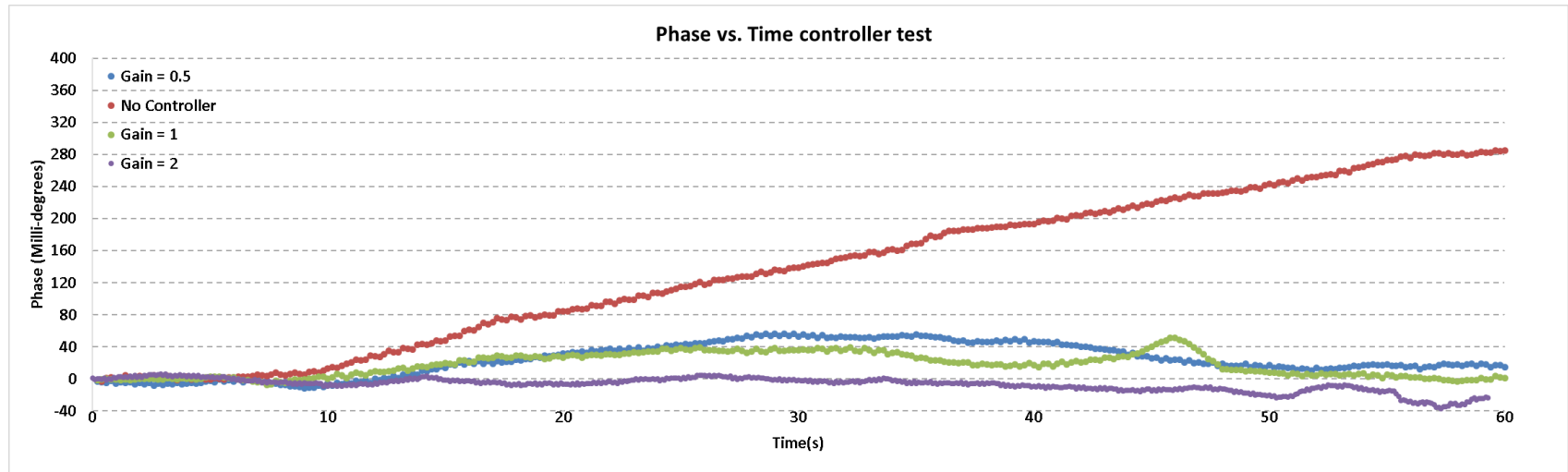


Prototype high power  
phase shifter built at  
Lancaster university, being  
used for current testing

# Prototype Phase Shifter Performance

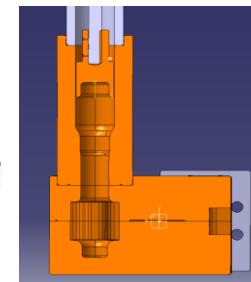
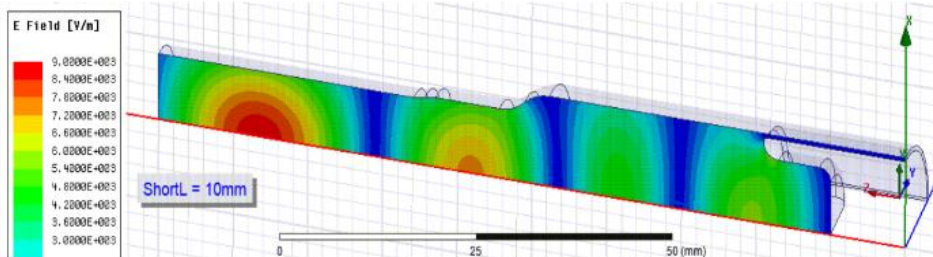
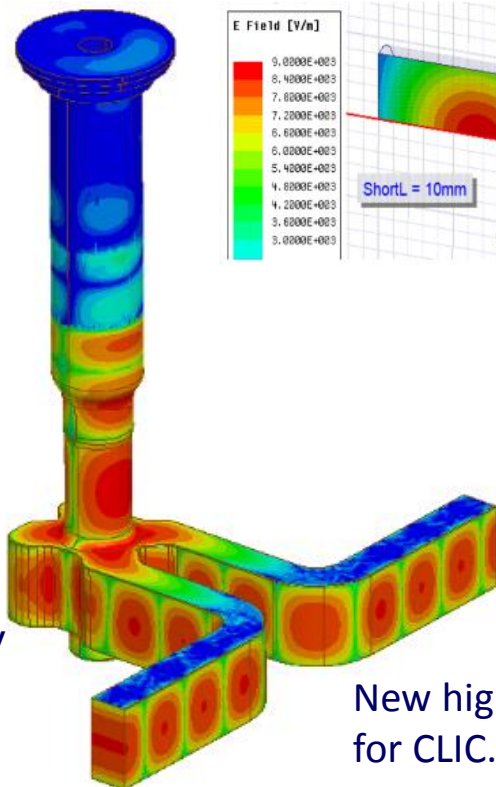
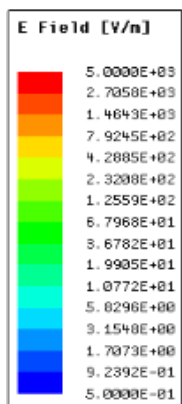






- PI controller implemented to control phase shifter – Localised heating applied to waveguide at the same temperature – different gains for controller tested
- Controller shown to be able to bring phase back to phase set point using phase shifter
- More work to be done to optimise controller
- Seeing random phase spikes – source needs to be found and eliminated

# Lasted Phase Shifter Design



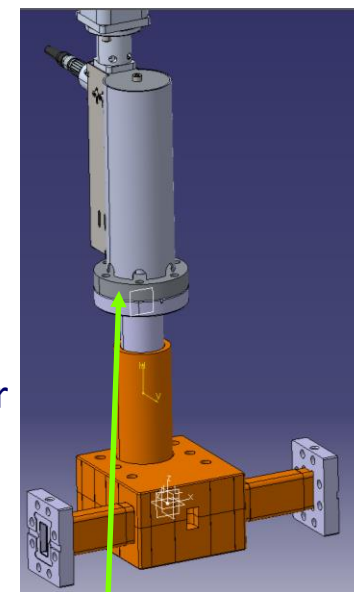
Converts waveguide TE<sub>10</sub> mode to two polarisations of the TE<sub>11</sub> circular waveguide mode.

Design – Alexej Grudiev  
CLIC – Note – 1067

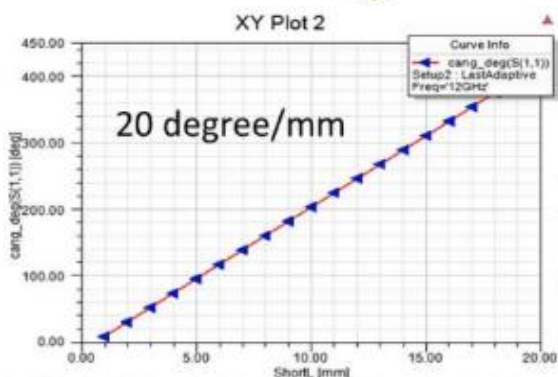
New high power phase shifter developed at CERN for CLIC. Design allows for integration of a stepper motor and piezo actuator giving solutions for the fast and slow phase shifters required.

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.



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



- ❖ 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
- ❖ Controller implemented to keep phase difference constant

# Future work

- ❖ Optimize controller
- ❖ Put full waveguide length into environmental chamber to monitor temperature drifts
- ❖ Investigate vibration effects on and near waveguide
- ❖ Possible high power tests at CERN of new phase shifter in waveguide when completed

## Thanks for listening!