The Cockcroft Institute
of Accelerator Science and Technology

BDS Crab cavity system

Graeme Burt on Behalf of Lancaster, ASTeC and CERN
Lancaster University, Cockcroft Institute
CERN-UK CLIC review Oct 2013

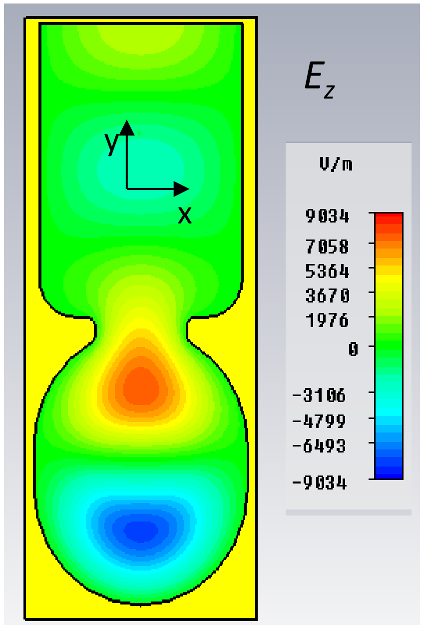
LANCASTER UNIVERSITY

Science & Technology Facilities Council

Objectives:

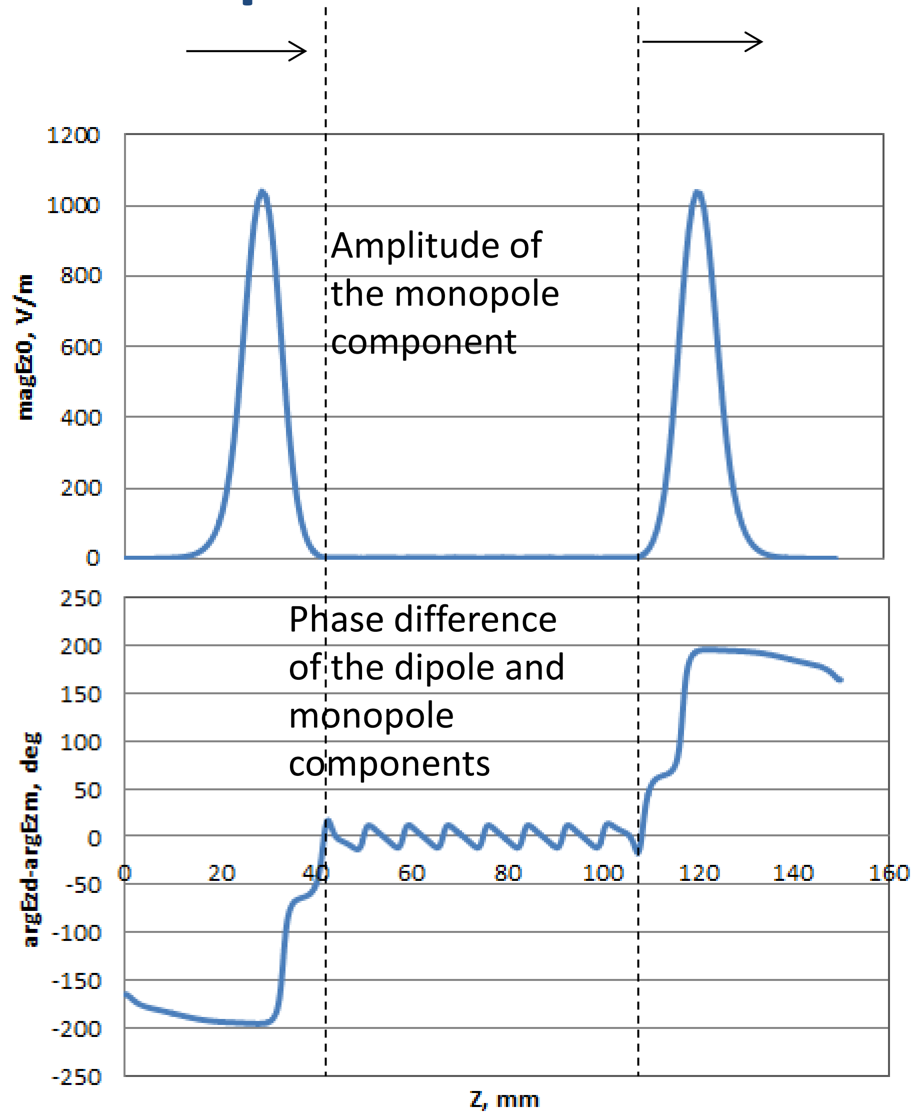
- Calculate wakefield effects for CLIC beams and analyze alignment tolerances.
- Optimize crab cavity damping structures.
- Design and fabricate a crab cavity appropriate for high gradient testing at CERN
- Feasibility studies and associated measurements for the Crab RF distribution system.

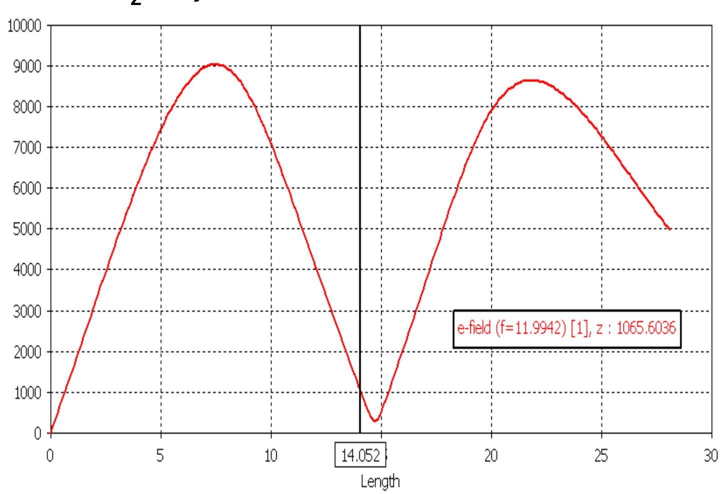
Single-feed coupler



$absE_z$ x y @ end cell

- Coupler offsets the mode centre in the end cells, causing an on-axis monopole component
- This causes a voltage along the beam axis Vz(0)~ 63 kV for 13.35 MW input power





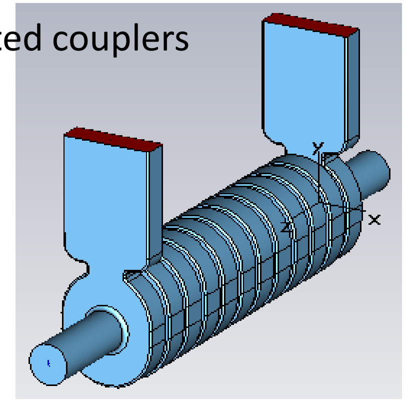
Monopole cancellation

- If we have a phase shift ϕ between the dipole and monopole components in the end cell the voltage is
- $V_m = e^{-i\phi} + e^{i\phi} = \cos\phi$
- The imaginary parts always cancel. If the phase shift is 90 degrees then the full voltage cancels.

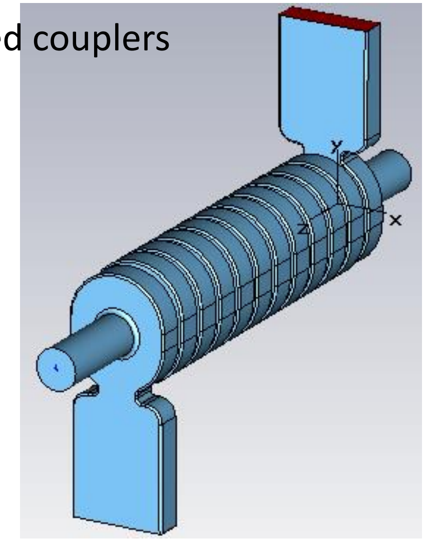
- However if we rotate the couplers we change the monopole phase by 180 degrees but not the dipole
- $V_m = e^{-i\phi} - e^{i\phi} = i \sin\phi$
- The real parts always cancel. If the phase shift is 0 degrees then the full voltage cancels.
- Its not quite this simple as the field profiles in the cells are not mirrored

BUT IS CANCELLING THE VOLTAGE ACROSS THE FULL STRUCTURE SUFFICIENT IN A TWS? IS THERE A TRANSIENT COMPONENT?

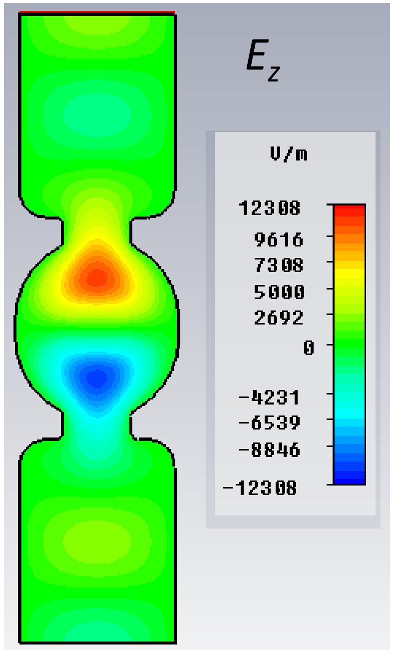
Unrotated couplers



Rotated couplers

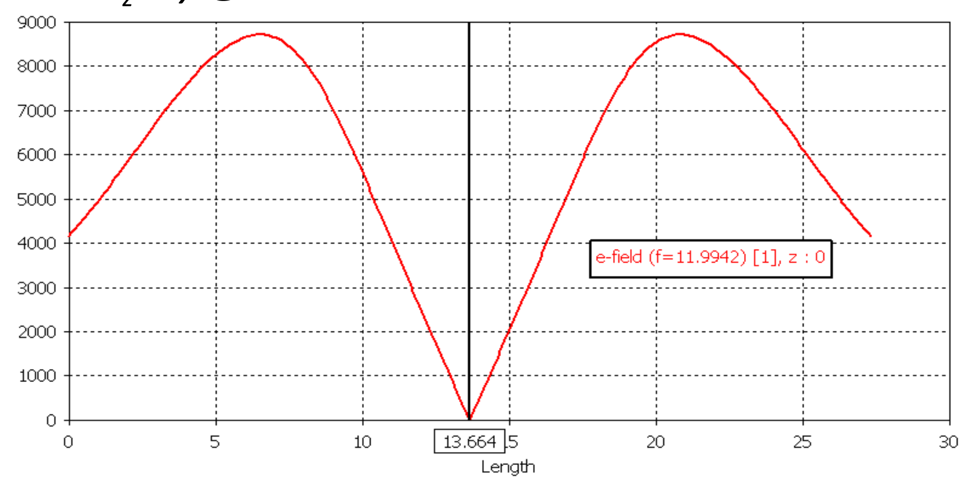


Dual-feed coupler

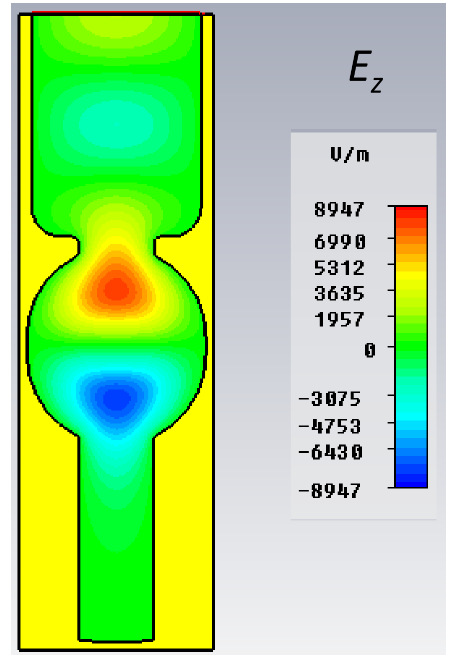


- Field has perfect symmetry about the coupler forcing the monopole component to essentially zero
- But needs two splitters which increases structure complexity

absE_zx y @ end cell

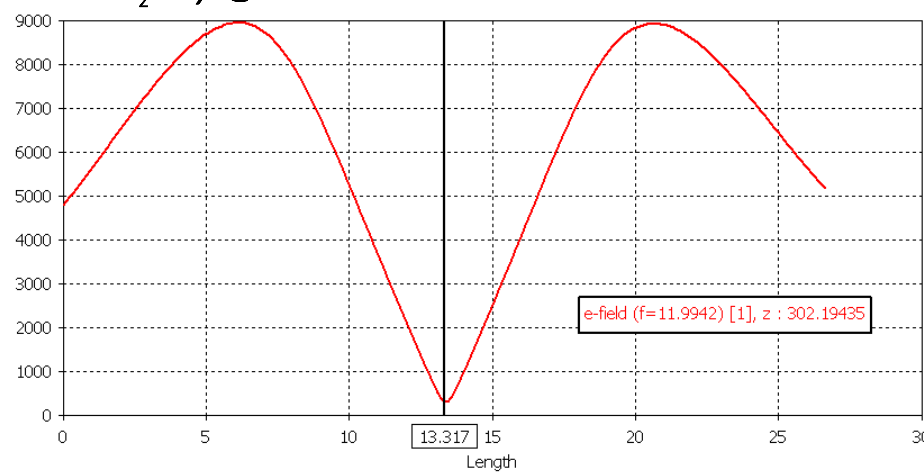


Dummy waveguide

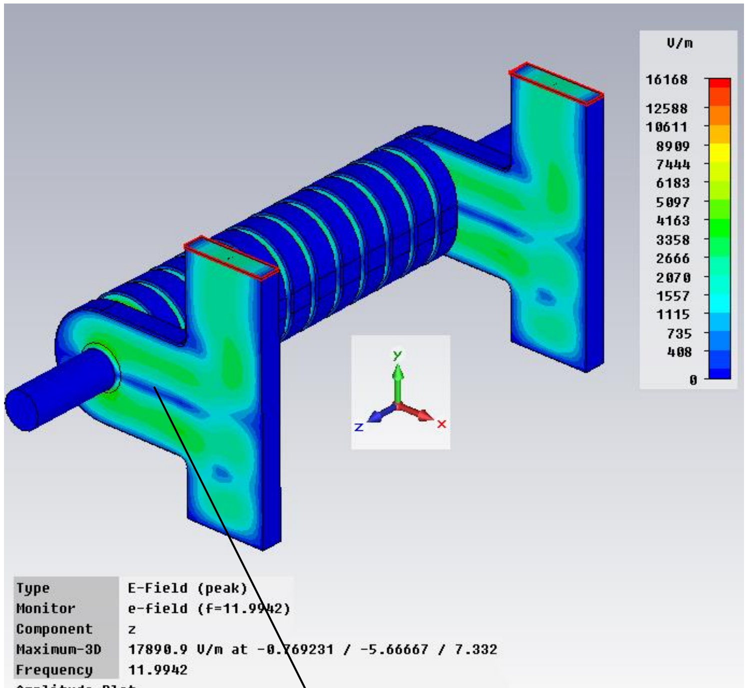


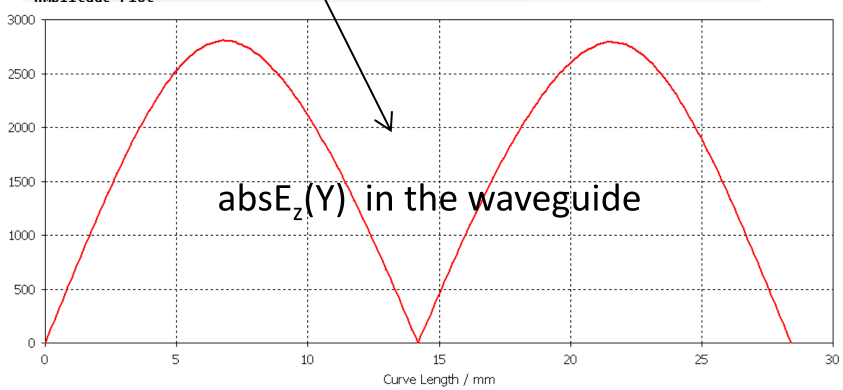
- A cut-off waveguide on the other side of the end cell can be used for mode centring
- On-axis voltage when couplers 0 deg Vz(0)~ 9 kV
- Causes a phase shift rather than full cancellation to the monopole component.

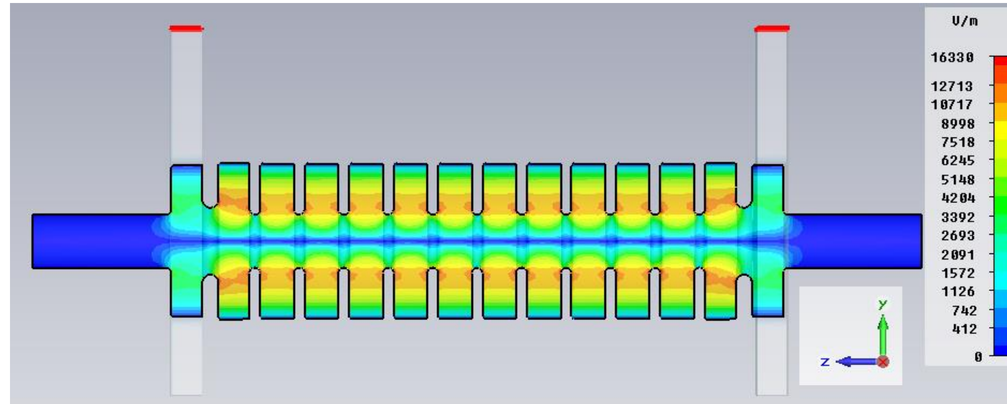
absE_zx y @ end cell

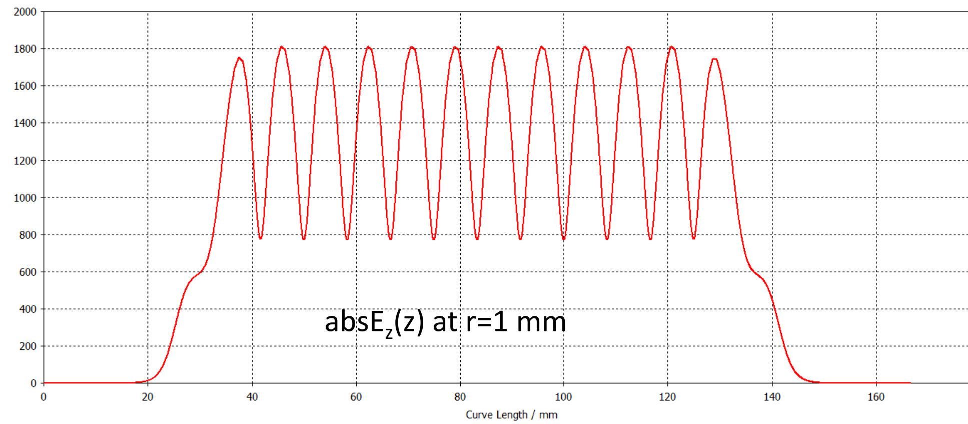


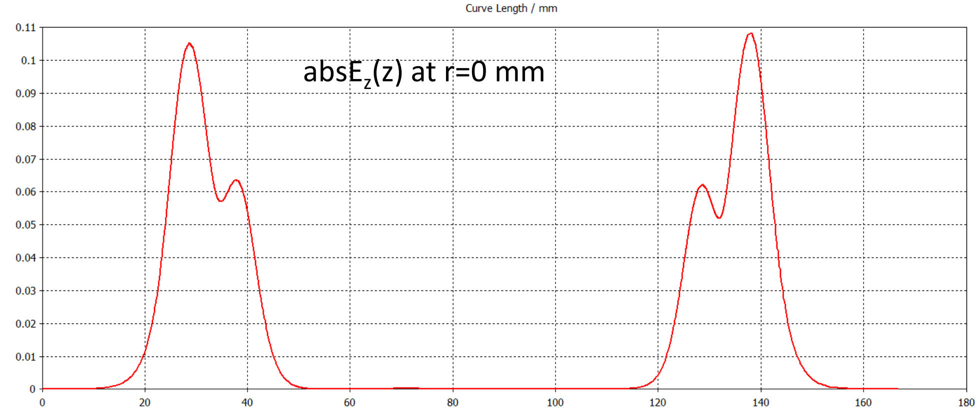
TE02 mode coupler



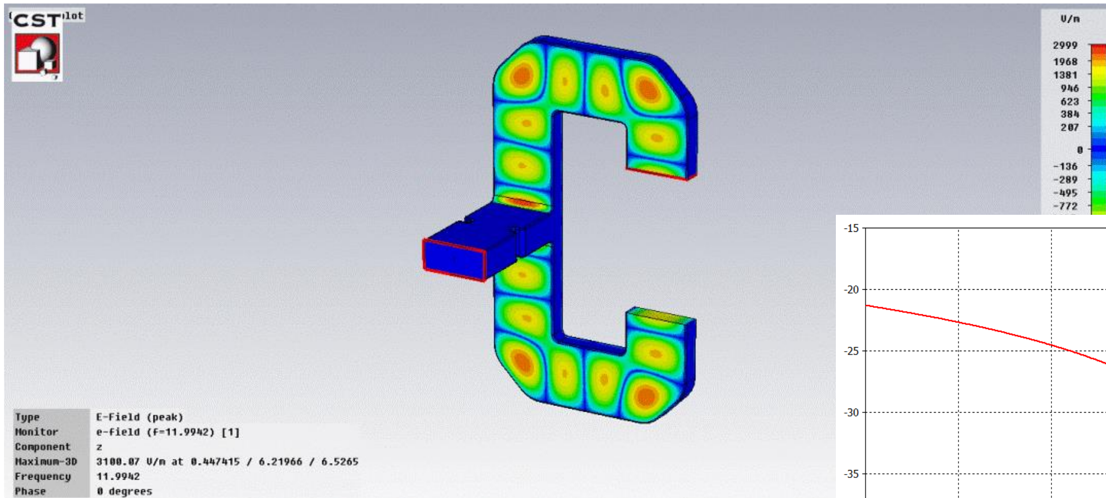


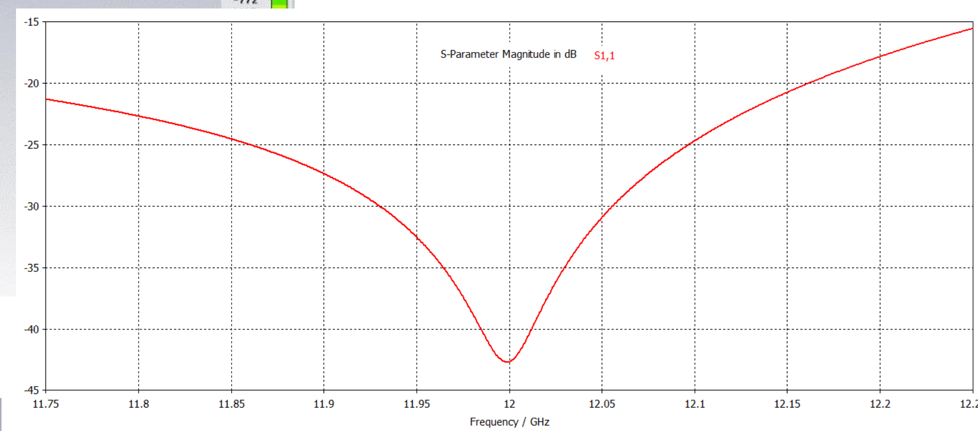


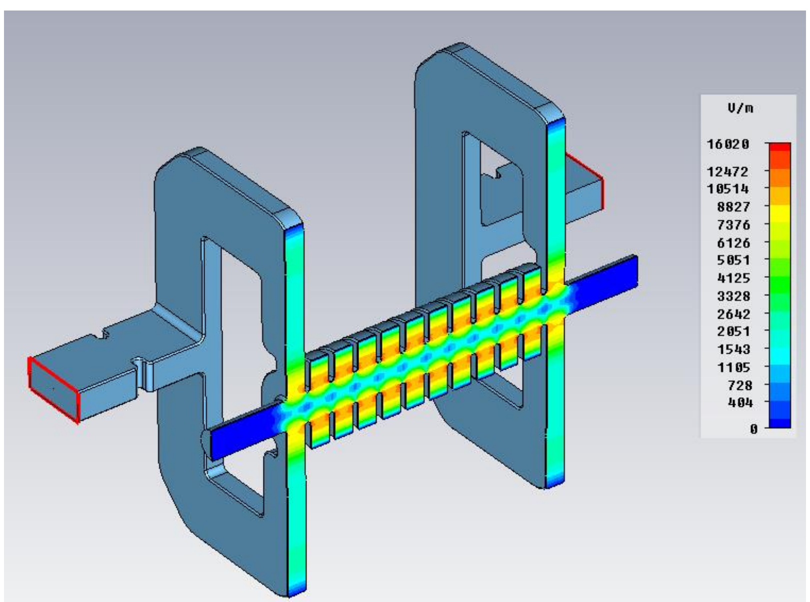




Symmetric dual-feed coupler





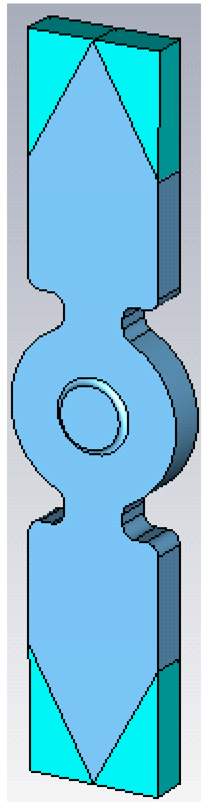


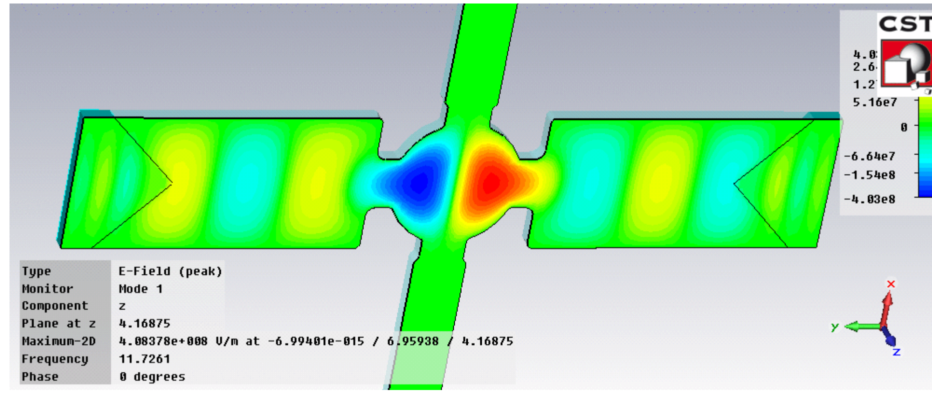
J. Wang et al., SLAC

Waveguide damping

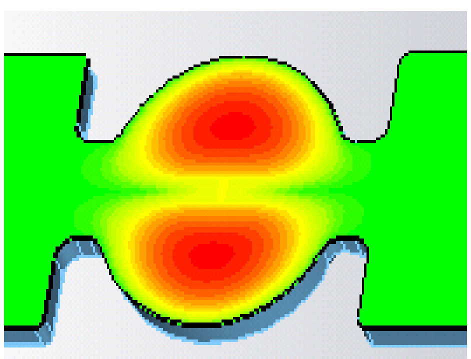
The simplest method of damping the vertical modes is to use a waveguide damper.

The crabbing mode does not couple to vertical waveguides however if the waveguide is at a slight angle to the vertical axis it will couple strongly if it is above cut-off.



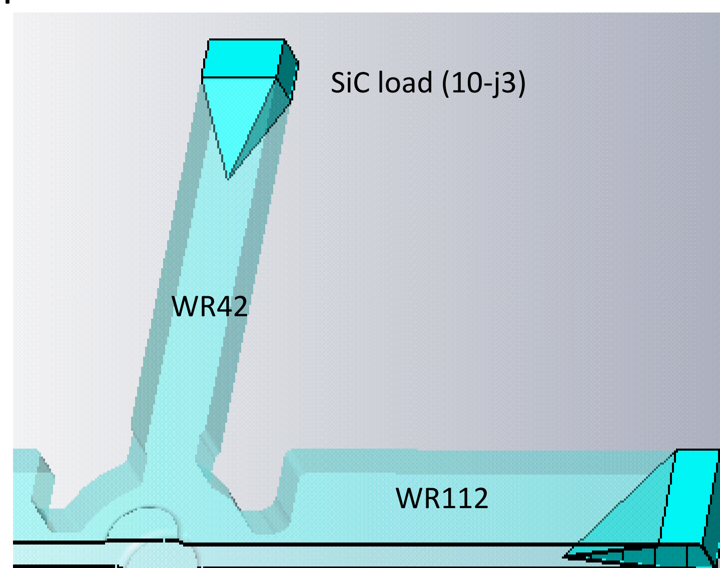


We can use a waveguide to damp the horizontal HOM’s as well as long as the crab is below cut-off

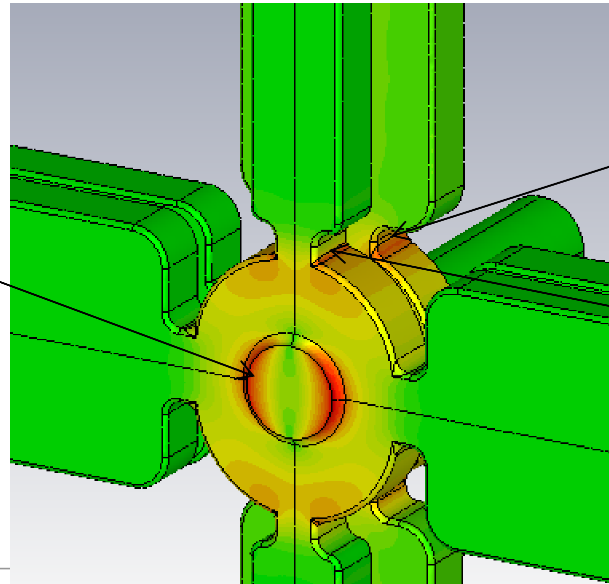


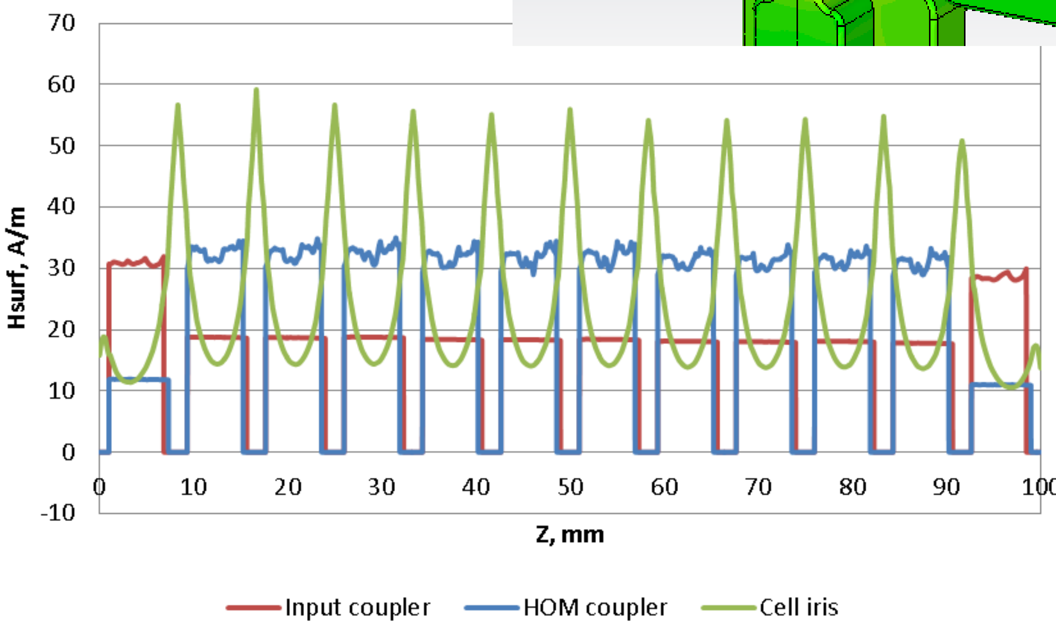
Crab

Mode	Crab	LOM	SOM
Q_{ext}	1e6	130	80



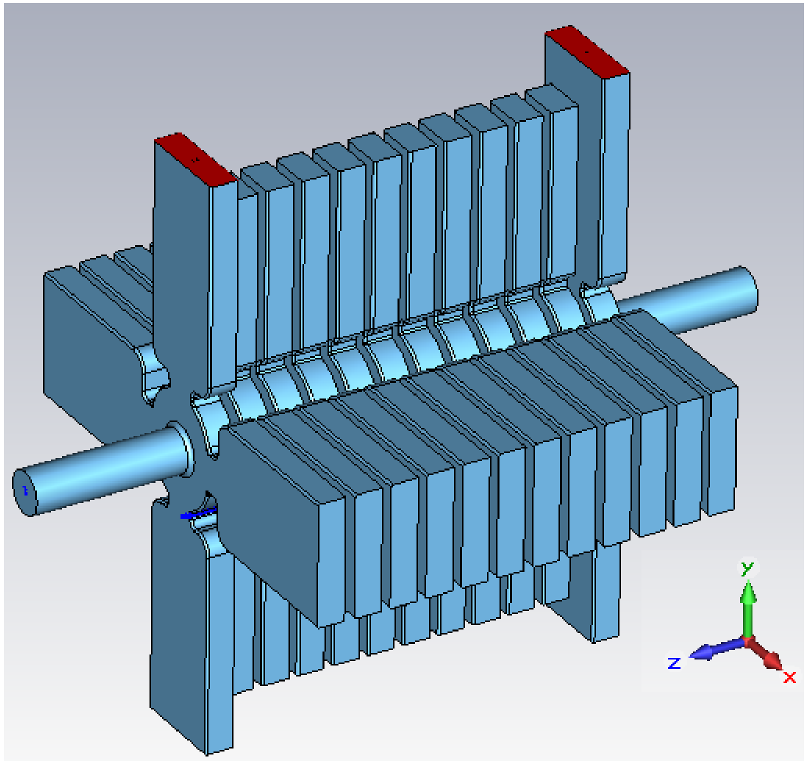
Surface magnetic field, A/m

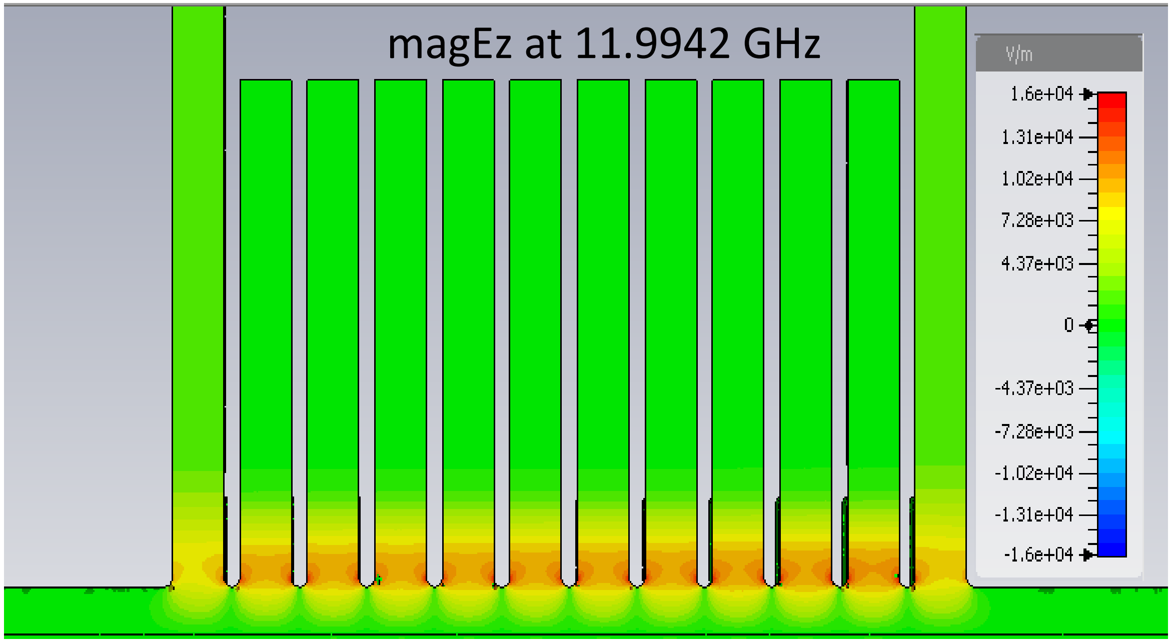




- Surface magnetic field distribution along the structure at 3 locations @ 1 W input power
- ΔT calculation done for 2.55 MV kick, 242 ns RF pulse

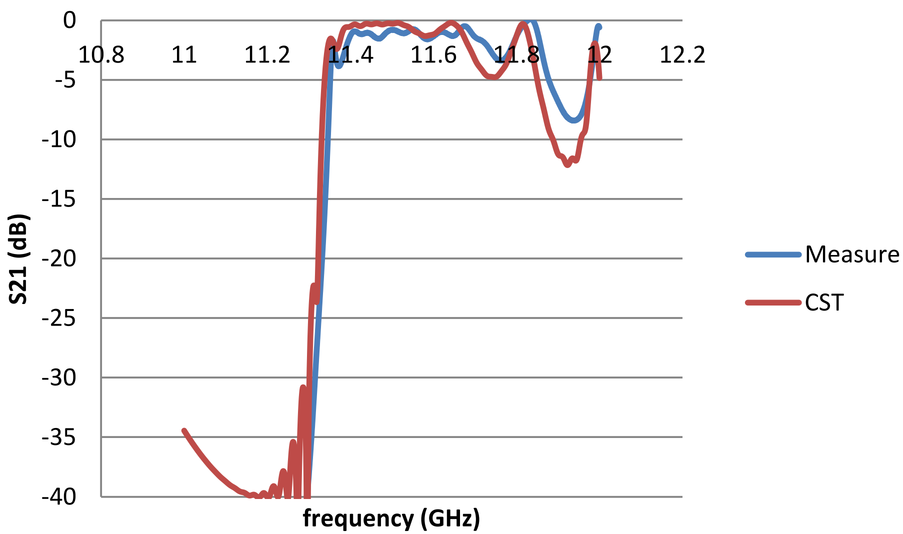
Full structure

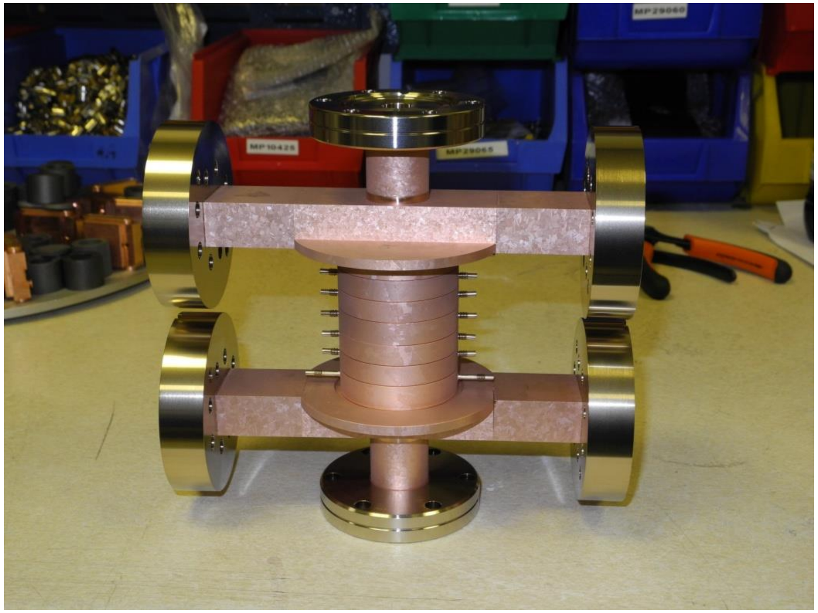


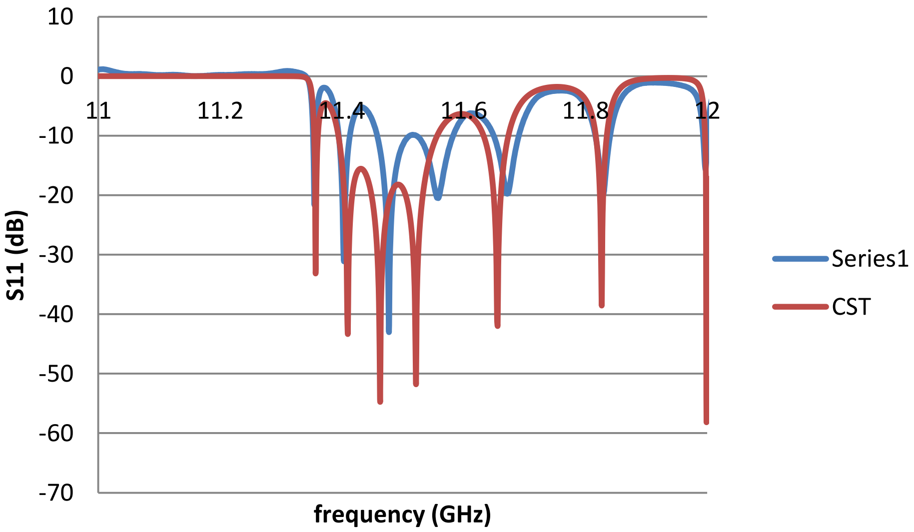


CLIC Prototype 1 - UK manufactured

The 1st CLIC crab cavity prototype has been manufactured by Shakespeare Engineering in the UK. Tolerance and surface roughness on single parts have been measured and are acceptable.



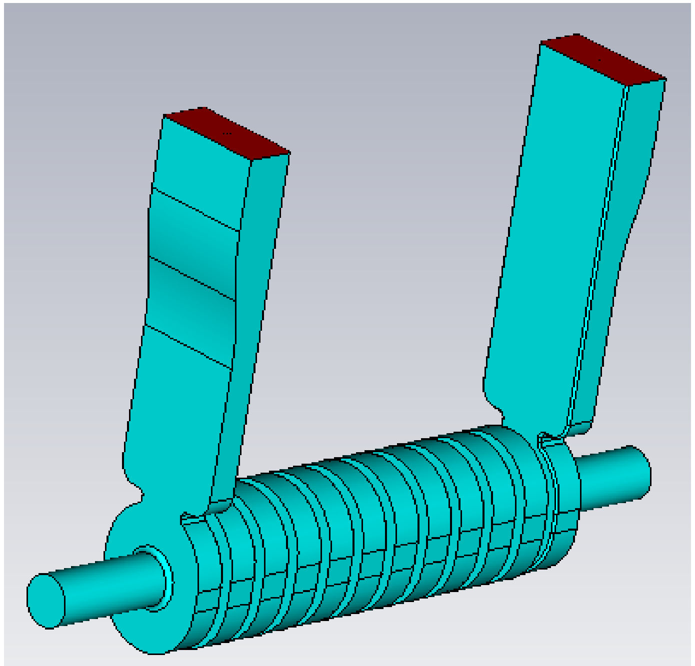




Structure is planned to be tested at SLAC in the near future.

- Test by measuring S-parameters at each port then combining to get the dual port F-parameters.
- Cavities have not been tuned yet.

Prototype 2 – CERN/VDL Built

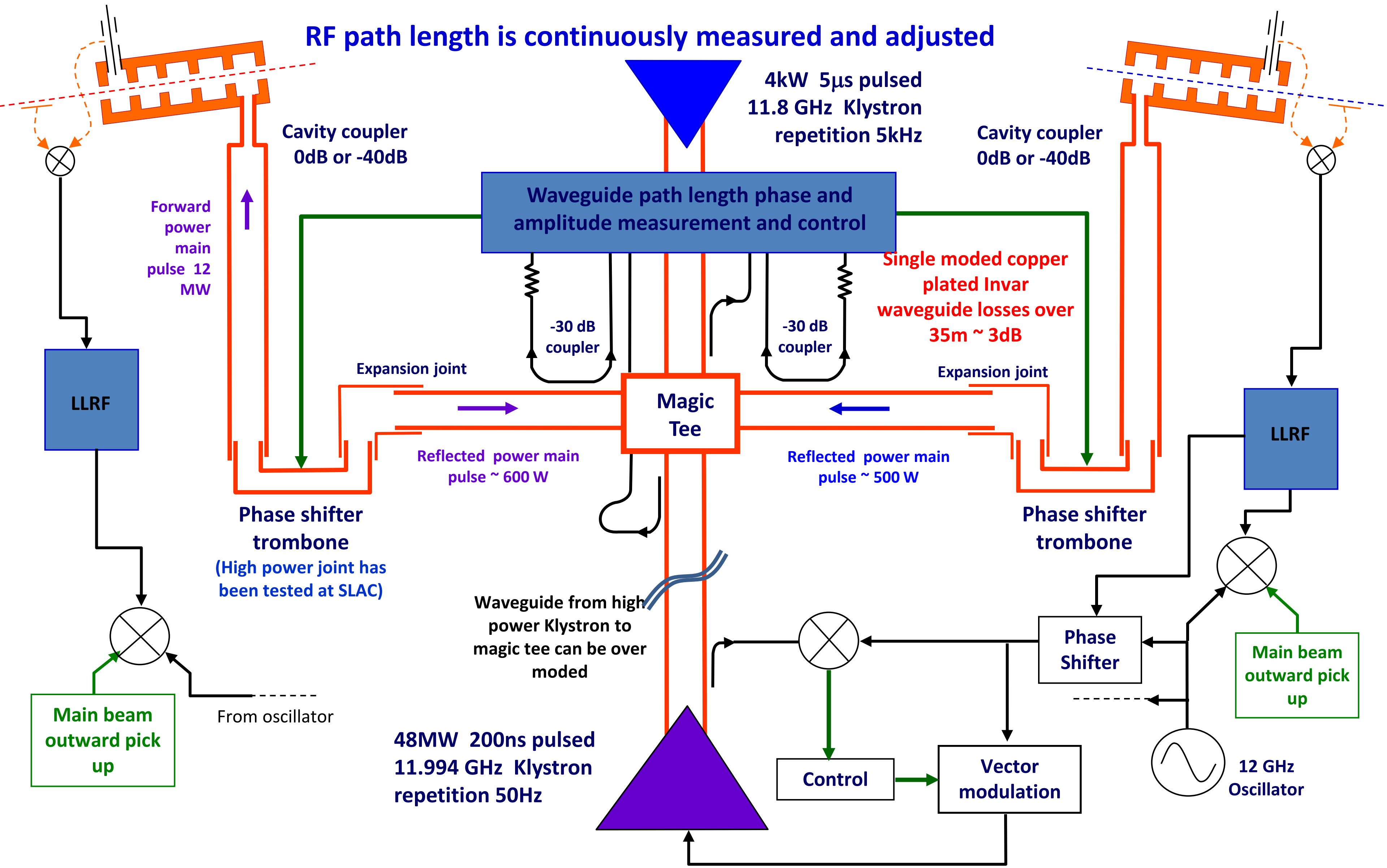


The structure being built for high gradient test at CERN has only a single feed as it will not see beam.

Cavity is being machined at VDL along with main linac structure to allow comparison of gradients.

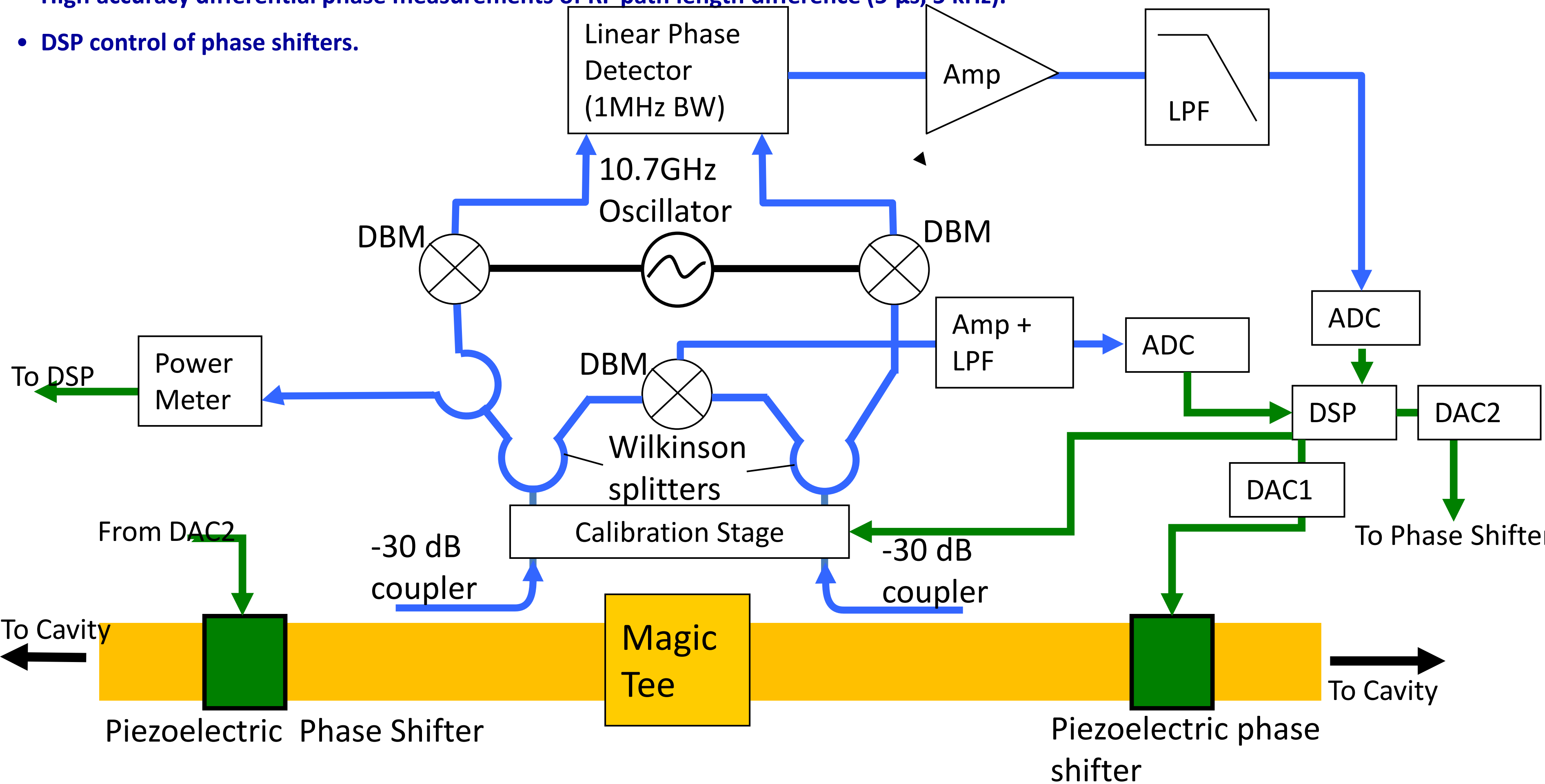
Size	
Number of cells	12
Total length (mm)	149.984
Active length (mm)	99.984

Revised Crab Synchronisation Scheme



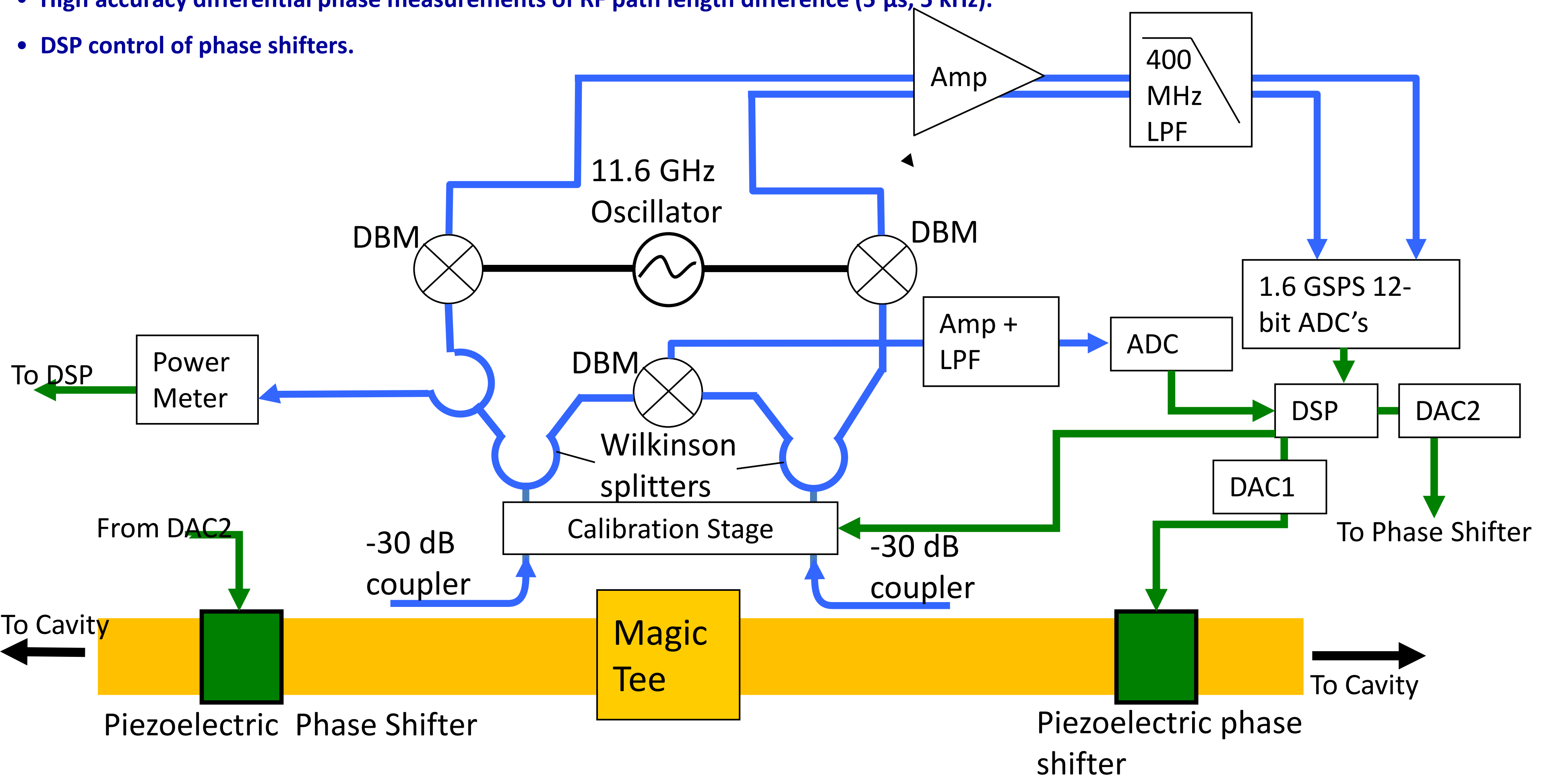
LLRF Hardware Layout (Low BW)

- **Fast phase measurements during the pulse (20-30 ns).**
- **Full scale linear phase measurements to centre mixers and for calibration.**
- **High accuracy differential phase measurements of RF path length difference (5 µs, 5 kHz).**
- **DSP control of phase shifters.**



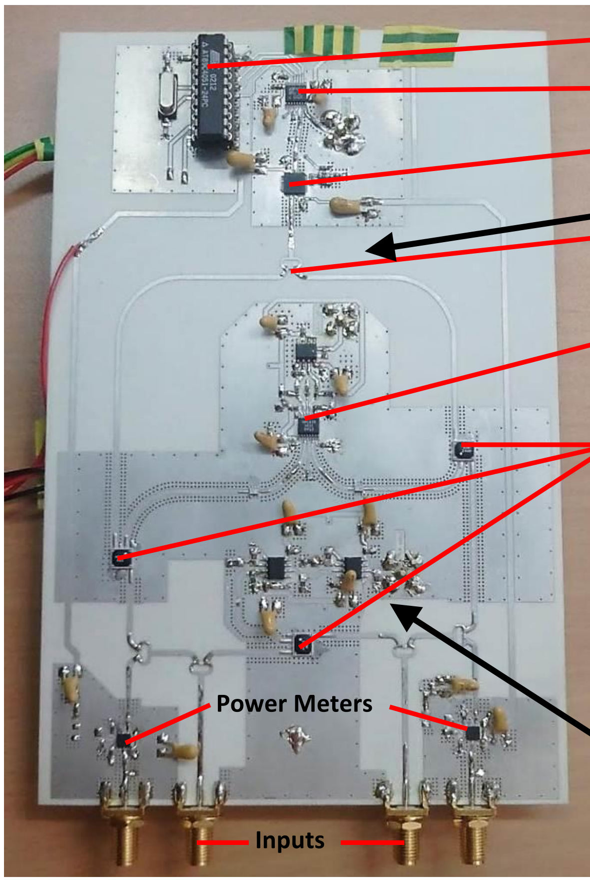
LLRF Hardware Layout (High BW)

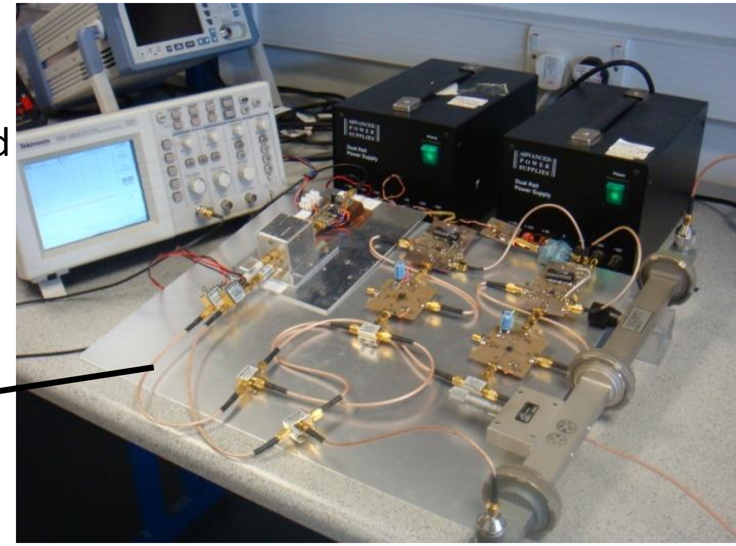
- **Fast phase measurements during the pulse (50MHz).**
- **400MHz direct sampling to centre mixers and for calibration.**
- **High accuracy differential phase measurements of RF path length difference (5 µs, 5 kHz).**
- **DSP control of phase shifters.**



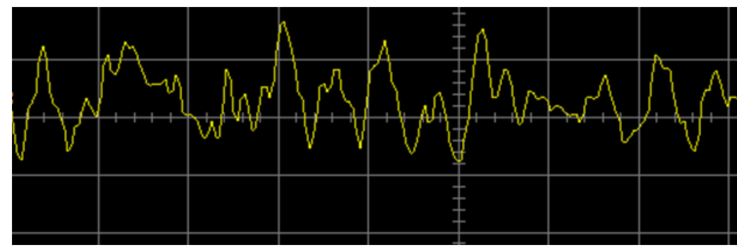
Board Development and CW tests

Front end electronics to enable phase to be measure during the short pulses to an accuracy of 2 milli-degrees has been prototyped and dedicated boards are being developed.

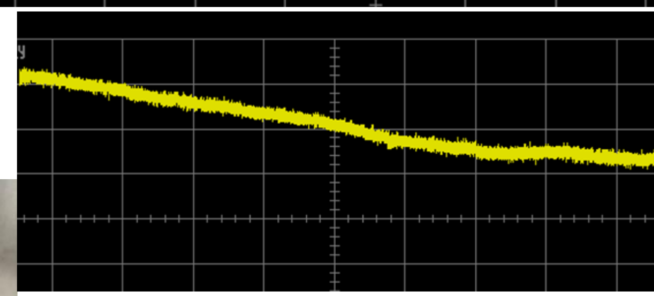




400 ns span:
RMS: 1.8 mdeg
Pk-Pk: 8.5 mdeg

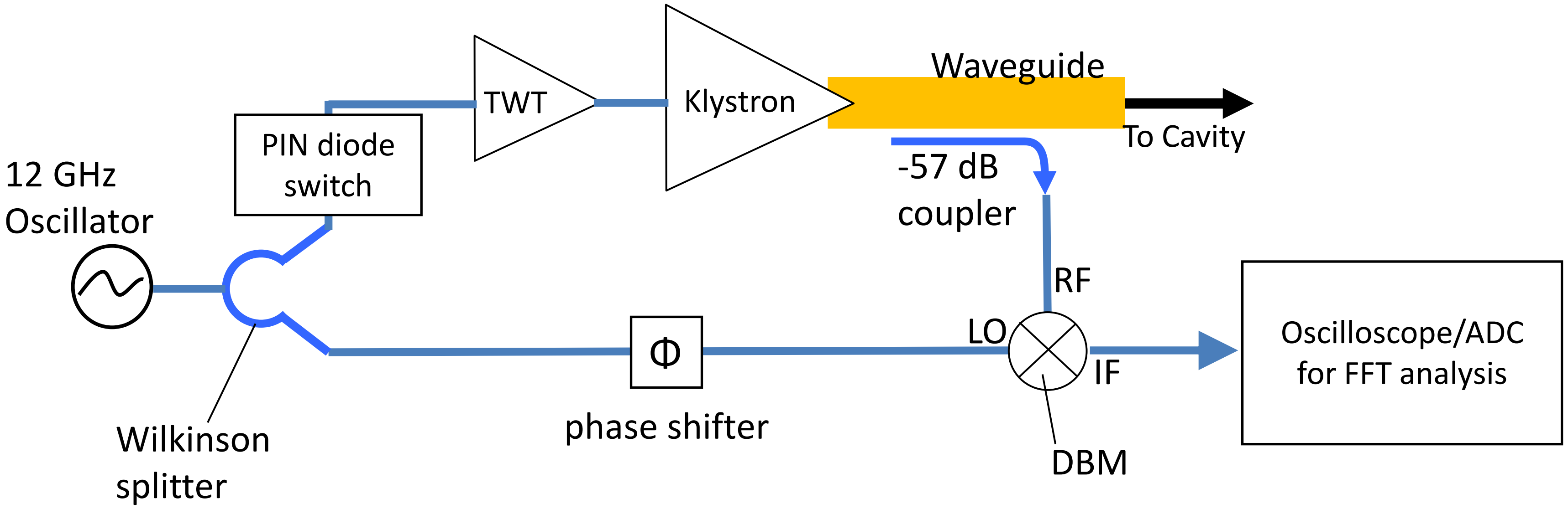


90 s span:
Drift rate : 8.7 mdeg/10s
Total drift: 80 mdeg



Klystron phase noise

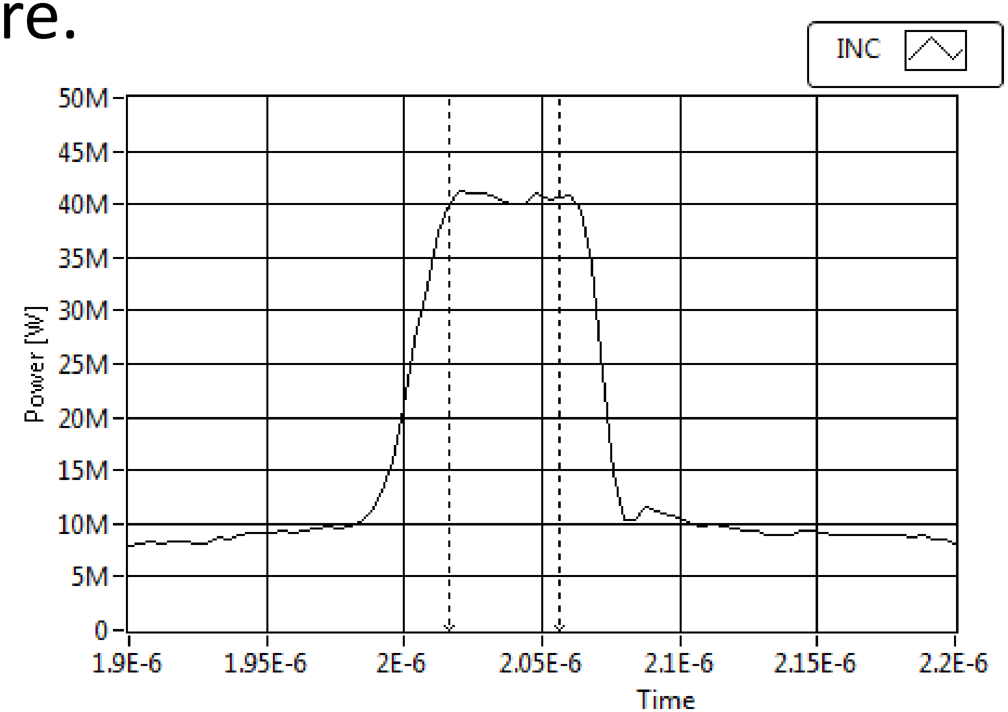
- Can use a standard method to measure the phase stability of the klystron.
- Reference source is split such that its phase noise is correlated out by the mixer for both channels.
- Phase shifter adjusted as to bring RF and LO inputs into quadrature.
- Digital scope or ADC and FPGA/DSP preforms FFT analysis, to obtain phase noise curve.
- Experiment can also be repeated for different lengths of waveguide to ascertain the effects of waveguide dispersion.



Measurement requires good amplitude stability as any AM will be present in the IF.

Observed Klystron Stability

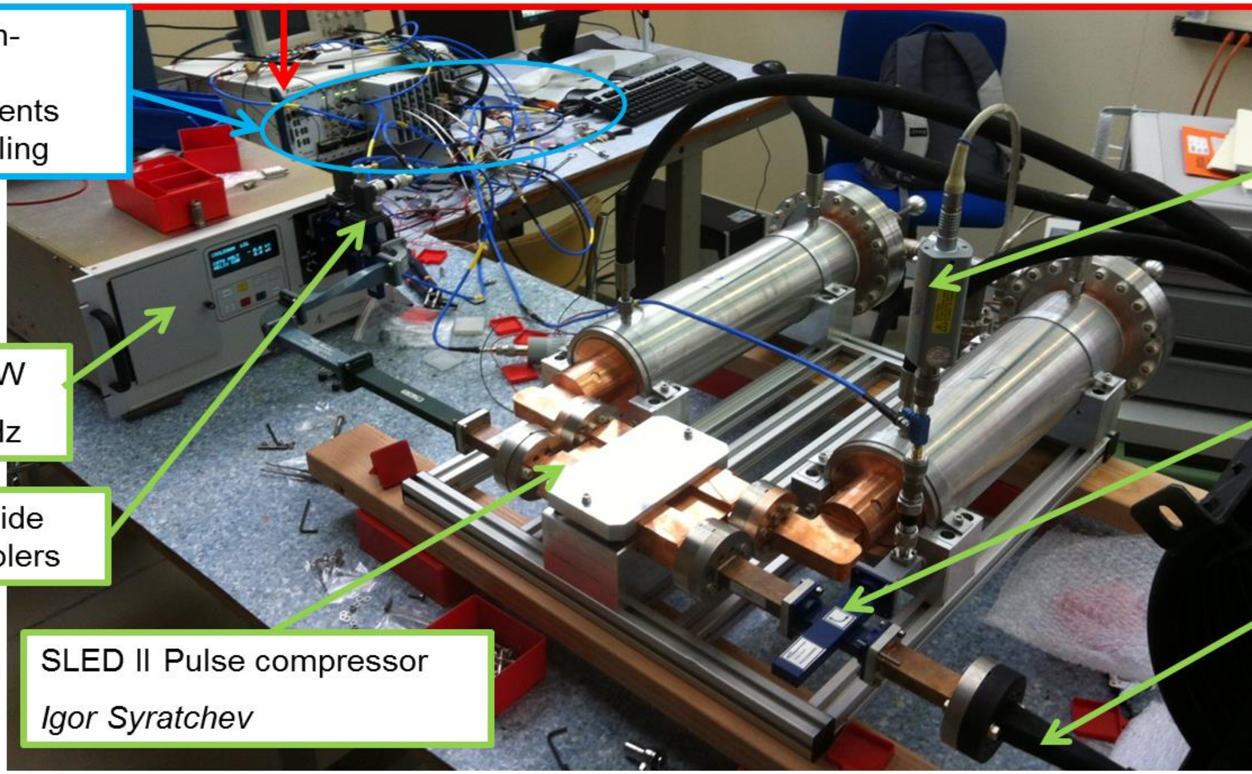
- Observed **~5%** amplitude jitter on the output of the klystron. → This was due to a mismatch in the pulse forming diode in the LLRF network and a triggering error in the ADC firmware.
- Amplitude jitter reduced to **~1-2%.**
- Phase measurements will be performed in the coming weeks.



The SLED

National Instruments PXI crate containing:

- 2 CW generators for the LOs.
- Vector modulator (up to 6.6GHz) with 200 MSPS I/Q generator
- 5Chs 1.6GSPS 12-bit and 4Chs 250MSPS 14-bit ADC each connected to FPGAs.
- 200 MHz digital I/O board for interlock and triggering signals.



Pulse compressor stability problems

Implementation of pulse compressor stabilization routine and AGC systems end of 2012 increased output power stability and system reliability:

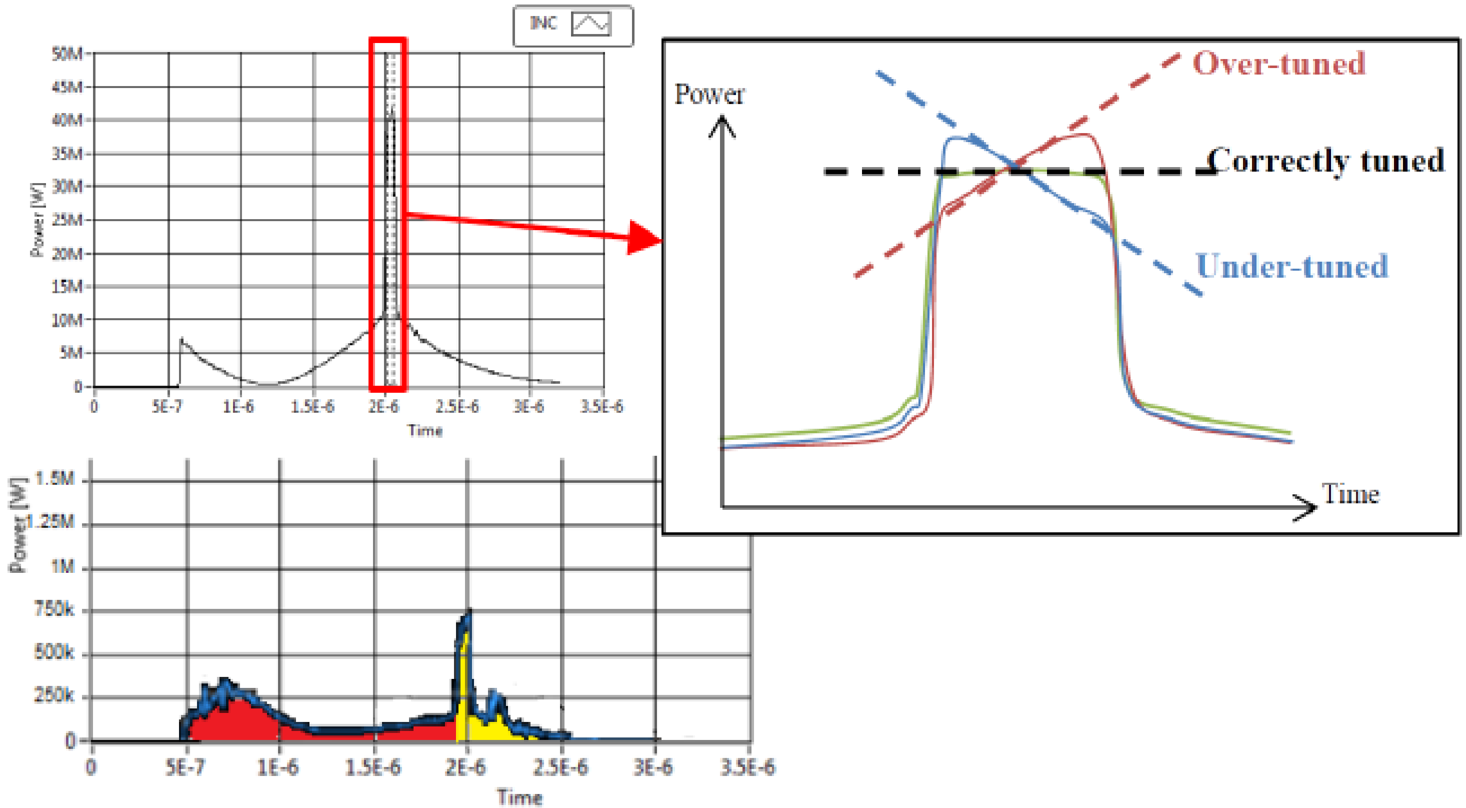
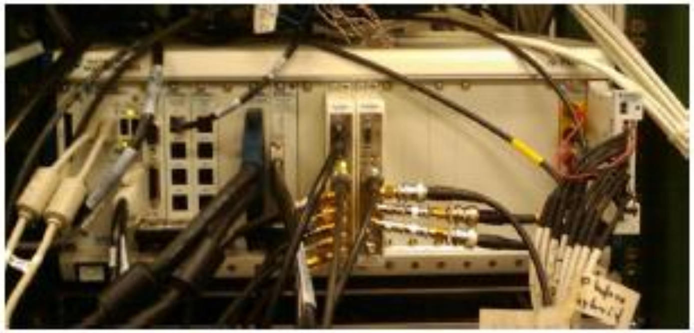


Figure 2 shows a typical, compressed output pulse taken during klystron operation (top left), with expanded views of the peak for different tuning regimes (right). Also shown is the reflected power back to the klystron from the pulse compressor (bottom left).

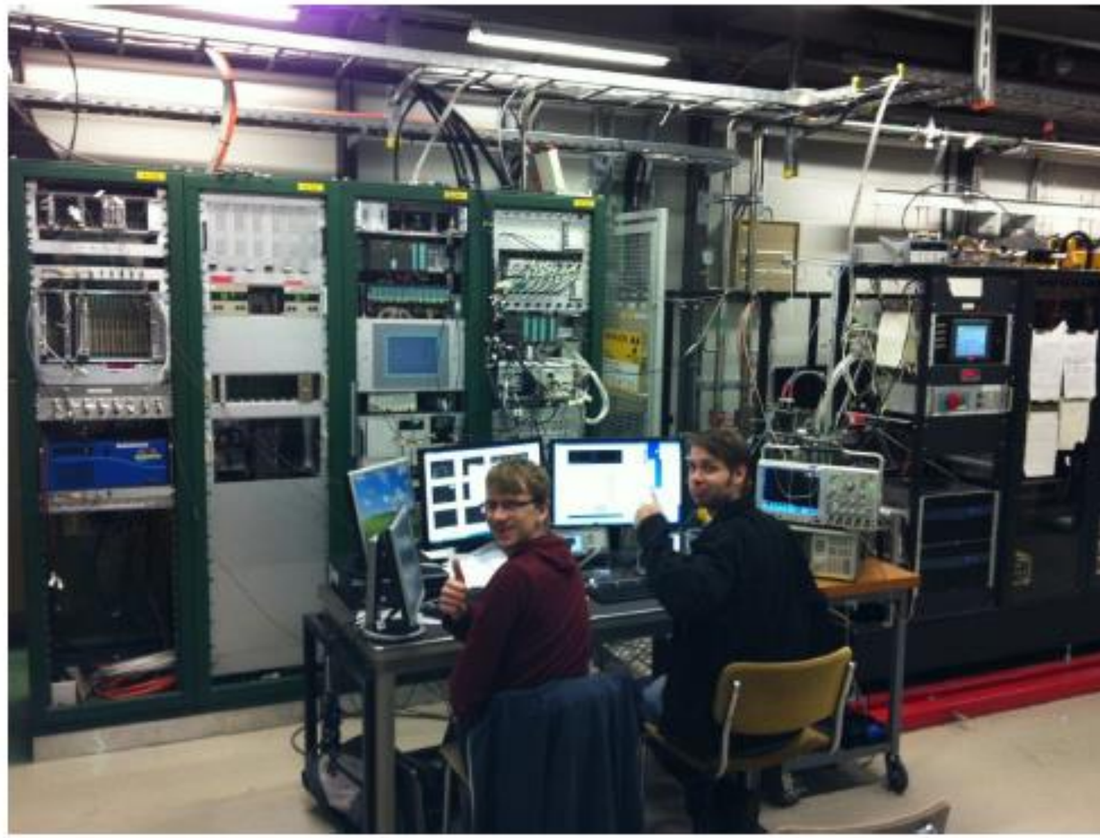
Ben Wooley and Joseph Tagg

The final X-box1 RF layout

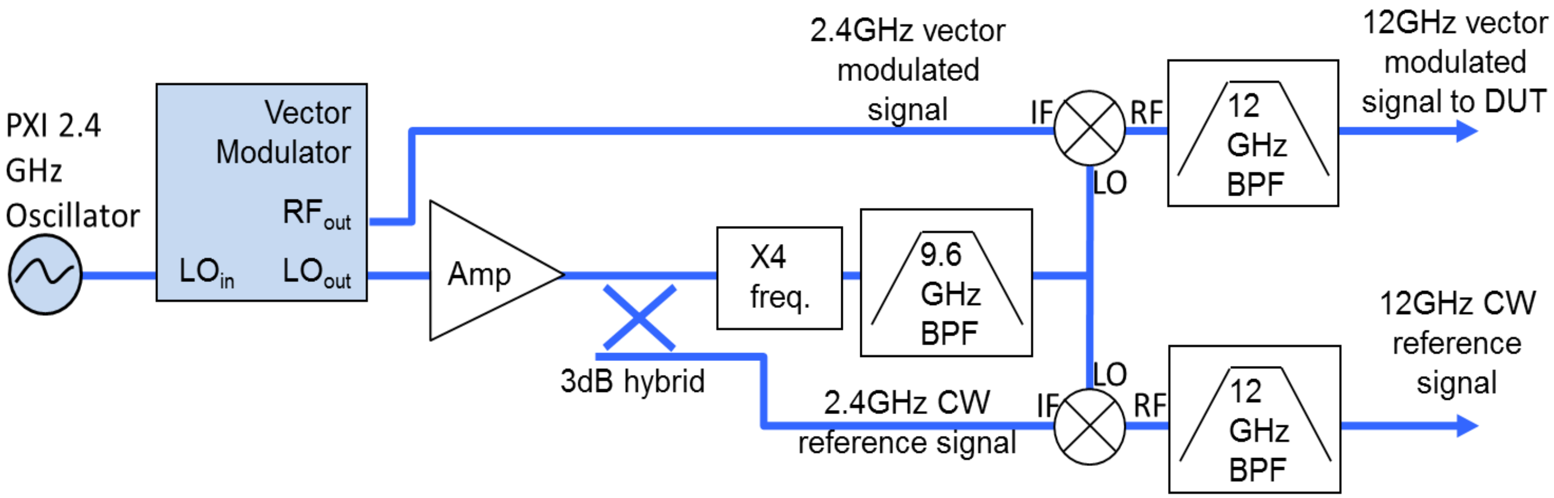
Due to the delays caused by the klystron repairs, the conditioning software based on the CERN control system could not be finished ➔ Urgent need for control, interlock and feedback systems!
➔ Decision to use a National Instruments PXI based system for all Xbox-1 controls and DAQ



- 8ch 250MSps/s 14 bit ADCs for RF (log detectors) and DC sampling, one FPGA for 4chs used for interlocking on reflected power and DC spikes
- I/Os for temp. gauges and interlock signals
- Stepper motor control and encoder read back
- Ion pump current readout for all pumps



XBOX2 input



shows the up-mixing stage needed to take the 2.4 GHz signal from the PXI crate up to the 12 GHz needed for input into the TWT/klystron.

Deliverables

- 1. Report on wakefield analysis.
  - Simulation coded but bug in code has caused issues
- 2. Report on structure design.
  - Full coupler study published in PRSTAB
  - Damping waveguides designed
- 3. Report on cavity fabrication and high power structure testing (if feasible).
  - Drawings produced and structure designed, out to tender soon
  - UK built structure developed a vacuum leak and is being reparied
  - Contract between CERN, UK and SLAC developing for High Power Testing
  - Xbox commissioned
- 4. Report on feasibility of synchronization schemes, future proof of principle phase synchronization experiments and high power klystron performance.
  - Improved crab RF synchronisation scheme devised
  - Analysis of waveguide expansion effects on phase stability
  - Work to improve measure RF measurement and control systems on XBOX1
  - Measurements of existing klystron stability
  - Development RF measurement systems and controls for XBOX2
  - Design of waveguide stability tests

Finance

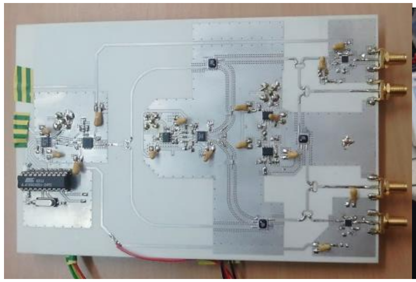
	Grant Budget	Actuals to date
STAFF		
Academic	2210	1043.63
Research	36532	19365.55
SUB TOTAL	**38742**	**20409.18**
NON STAFF		
Consumables	10000	713.42
Equipment	10000	5325.55
Other non staff	0	89.85
Travel	20000	6146.78
SUB TOTAL	**40000**	**12275.6**
INDIRECTS		
Estates	16089	7597.64
Indirects	37638	17794.75
SUB TOTAL	**53727**	**25392.39**
TOTAL FEC	**132469**	**58077.17**

PDRA left to get a job in Pilani Uni. Have made an offer to a potential replacement. Fully expect to spend full amount.

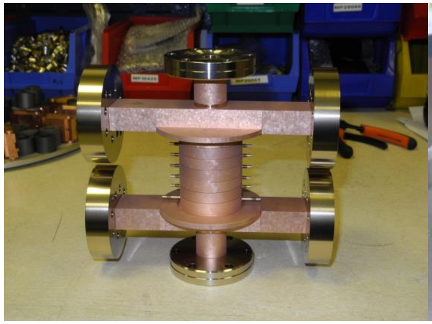
Saving travel for cavity tests, components will be ordered in the next months.

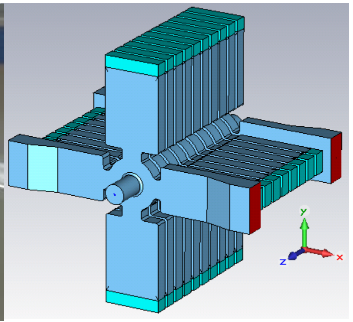
2.2 BDS Crab cavity system (Lancaster)

- This sub-task has two main goals
  - To understand and measure long-term phase stability in high power pulsed RF distribution and amplification,
  - Development work to improve RF measurements of phase and amplitude as required for the CLIC crab cavities and the X-box test stands.
  - Develop controllers for XBox




  - To develop SIC damping structures (in synergy with the main linac), simulate the full structure with wakes
  - High power test existing structures.





CLIC Crab High Gradient Testing

Cavities Built but not tested

- **Cavity 1**: UK manufactured, waveguide coupler, test of mid cells
- **Cavity 2**: Elliptical cells and on cell couplers. CERN manufactured.

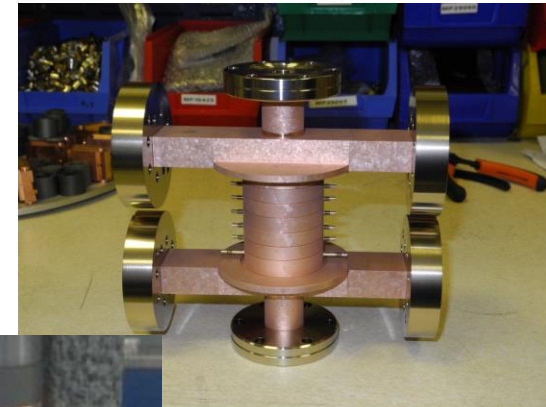
Cavities designed but not built (finished by end of year)

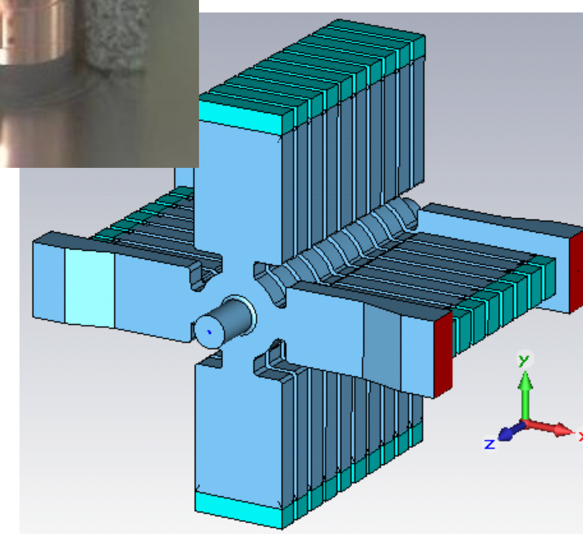
- **Cavity 3**: Final cavity design with damping waveguides (without loads)

Cavities not designed

- **Cavity 4**: Final prototype with HOM loads.

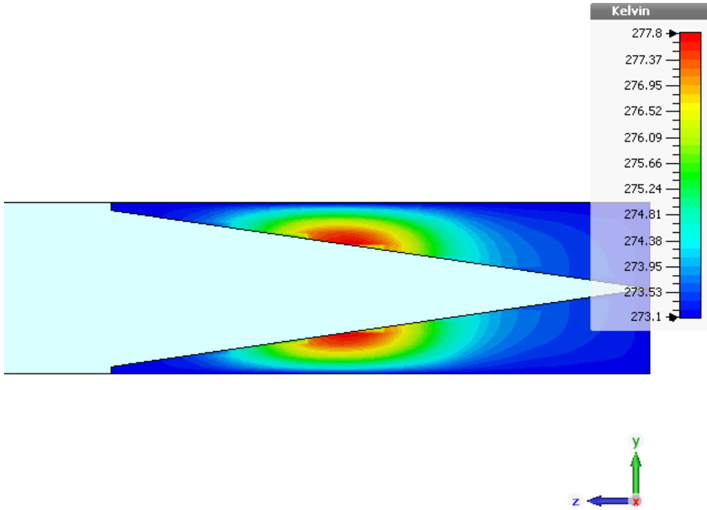
- By 2015 we plan to have designed all 4 cavities and build the first 3.
- Also will evaluate wakefields of final design

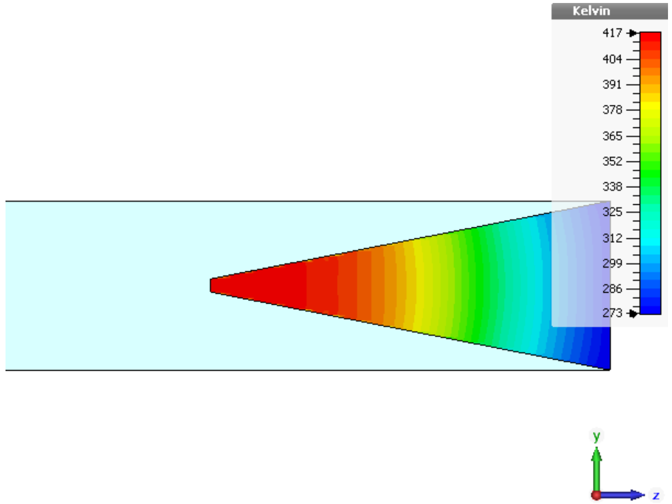


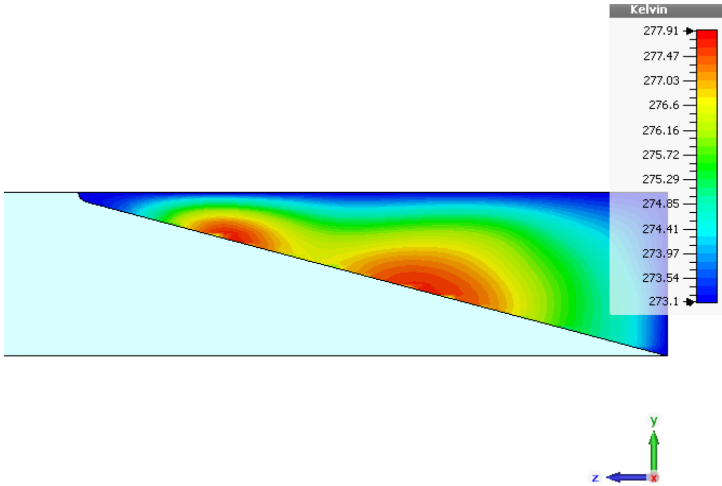


SiC Load Study

- Investigation of reflection and heating in various load shapes.
- Further work needed to investigate manufacture and cooling for a realistic structure.
- Highly synergetic with main linac but needs to work a lower frequency in a wider waveguide.

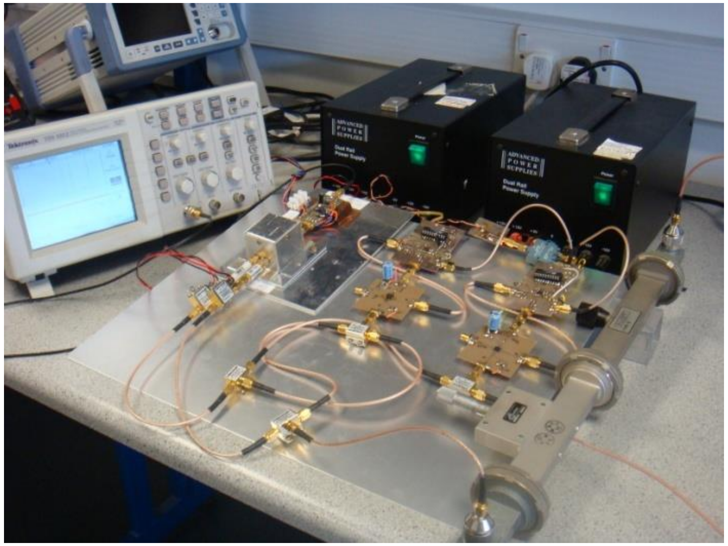






Phase stability and XBox

- Continued investigations into the phase stability of the 50 MW X-band klystron.
- Development of feed-forward and/or feedback system to stabilise the klystron's output.
- Continued characterisation of electronics to obtain stand alone phase measurement/correction system.
- Design/procurement of the waveguide components needed.
- Demonstration RF distribution system, with phase stability measurements.
- Perform phase stability measurements during the CTF dog-leg experiments.
- Measure phase across the prototype cavity during a high power test.



Deliverables:

- **2014: Perform experiments on CTF3 dogleg**
- **2014: Testing of initial structures at CERN and/or SLAC**
- **2015: Final design of SiC damping structures**
- **2015: Test structure with damping waveguides (no loads) at CERN**
- **2016: Production of improved phase measurement electronics**

Finances

Lancaster Staffing (man-months):

2.2 Crab Cavity:	*FY1*	*FY2*	*FY3*	*Total*
Faculty (Dexter)	**2**	**2**	**2**	**6**
RA1	**12**	**12**	**12**	**36**
RA2	**10**	**10**	**10**	**30**

Lancaster Resources (£k):

Crab Cavity:				
Materials	**2+3**	**2+3**	**2+3**	**6+9**
Travel	**5+10**	**5+10**	**5+10**	**15+30**

Two PDRA's, one working on the cavity and one on LLRF and Xbox.
Travel will allow both PDRA's to spend significant fractions of their time at CERN.