CLIC Crab Cavity

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CLIC UK collaboration meeting

CERN

May 2012

Combined Project Scope

REMAINING EUCARD1 TASKS (FP7)

- Gradient tests of a cell design excited in a dipole mode at SLAC
  - (Awaiting delivery from Shakespeare Engineering)
- Manufacture a multi-cell un-damped cavity for high power tests at CERN
  - (Disc manufacture is proceeding)
- Complete phase measurement sampling electronics
  - (Will complete by August)

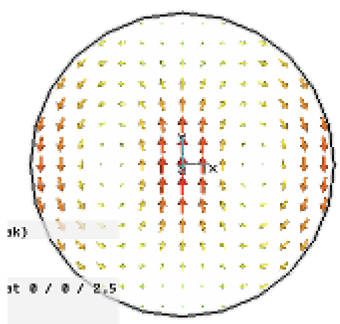
UK-CERN CLIC COLLABORATION PROJECT

- Development of a damped structure with racetrack/elliptical cells
  - (on going)
- Engineering design work to enable prototype cavities to be tests at CERN
  - (cooling, vacuum, mounting, instrumentation etc.)
- Experiments to understand stability of the RF distribution system
  - (PhD project starting with RF measurements on CTF3 use dog leg)
- R&D as necessary to improve stability of RF distribution system
  - (Some new ideas to present)

CLIC crab cavity specification

• Transverse space:	~1 m
• Bunch rotation angle:	10 mrad
• Travelling wave mode:	$2\pi/3$, 11.9942 GHz
• Voltage:	2.55 MV per cavity
• Available peak power at cavity:	14 MW
• Max peak surface field (absolute)	250 MV/m
• Max peak pulsed heating:	40 K
• RF tolerances for 98 % luminosity:	dV_{rf}/V_{rf}=2 %, $d\phi_{rf}$=22 mdeg

Use TM_{110h} pillbox crabbing mode



with vertical B field on axis, phased for zero B at bunch centre

The design process must also meet wakefield specifications and have a means to manage unpredictable beamloading

Cavity synchronisation

CLIC bunches ~ 45 nm horizontal by 0.9 nm vertical size at IP.

Cavity to Cavity Phase synchronisation requirement

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

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

So need RF path lengths identical to better than c Δt = 1.3 microns

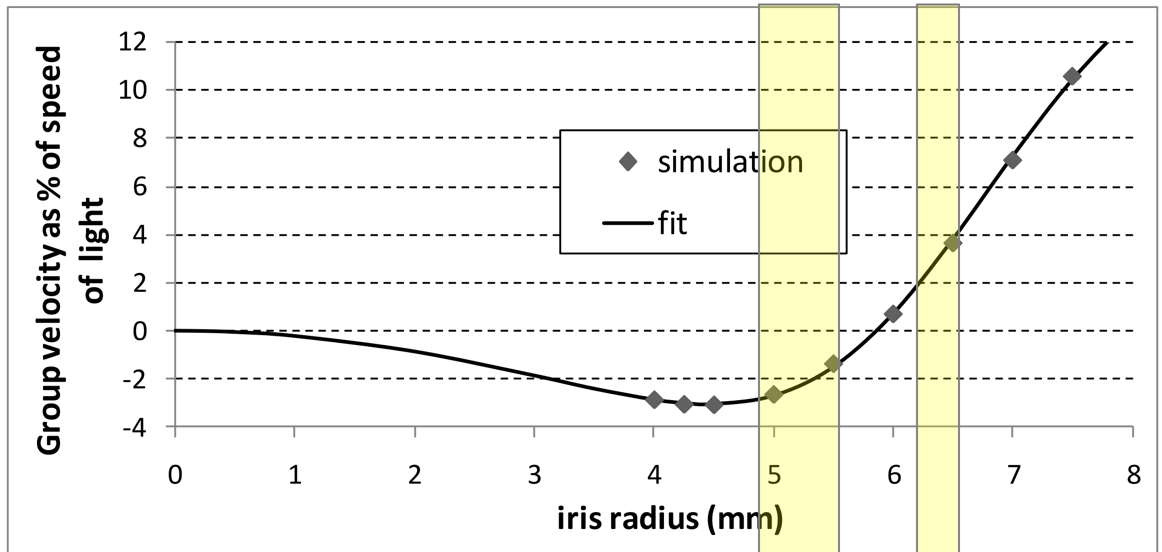
Beamloading and cell number

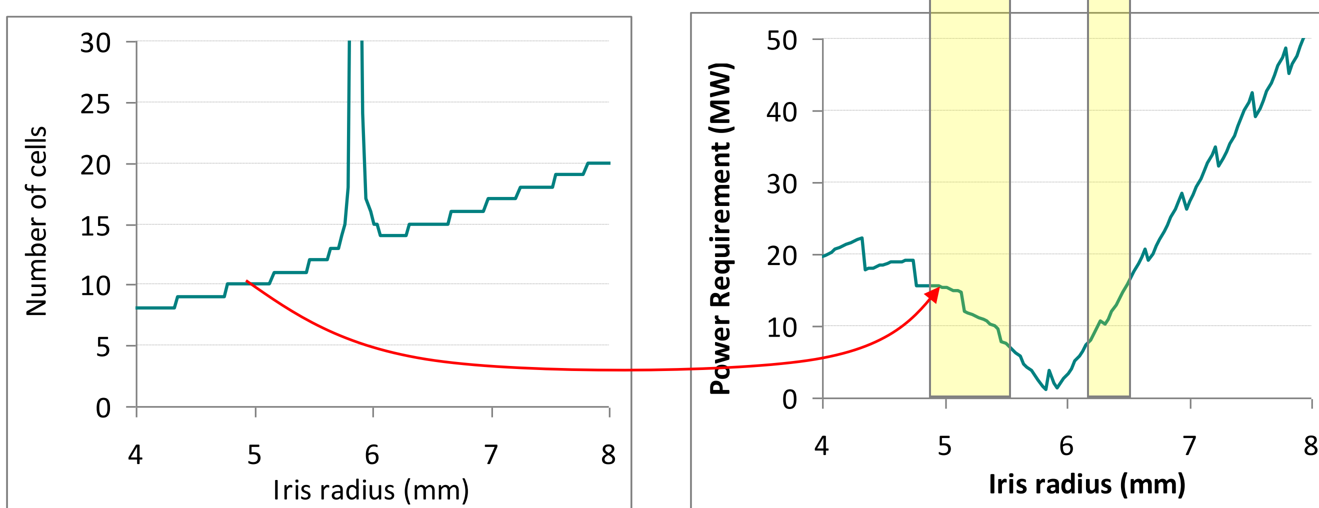
Manage beamloading by having high power flow or dissipation much high than expected loading

Can increase power convection by increasing the structure group velocity.

The group velocity depends on iris radius.

But have limited power (~15 MW) at cavity so can only increase the convection so much.

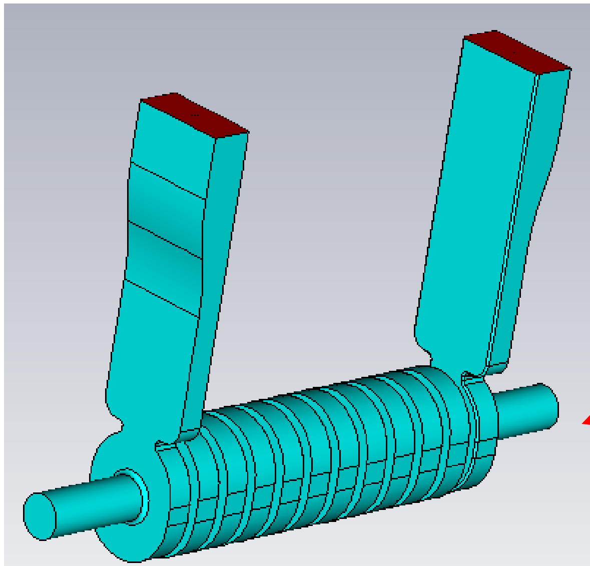


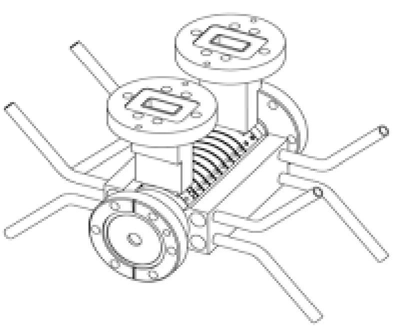


Ten cells is about about the minimum

Planned CLIC crab high power tests

Travelling wave 11.9942 GHz
phase advance $2\pi/3$
TM110h mode
Input power ~ 14 MW

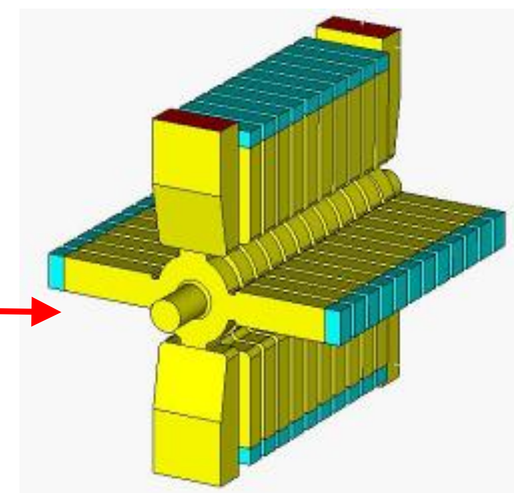




Test 1:
Middle Cell Testing – Low field coupler, symmetrical cells. Develop UK manufacturing.

Test 2:
Coupler and cavity test – Final coupler design, polarised cells, no dampers. Made with CERN to use proven techniques.

Test 3:
Damped Cell Testing – Full system prototype

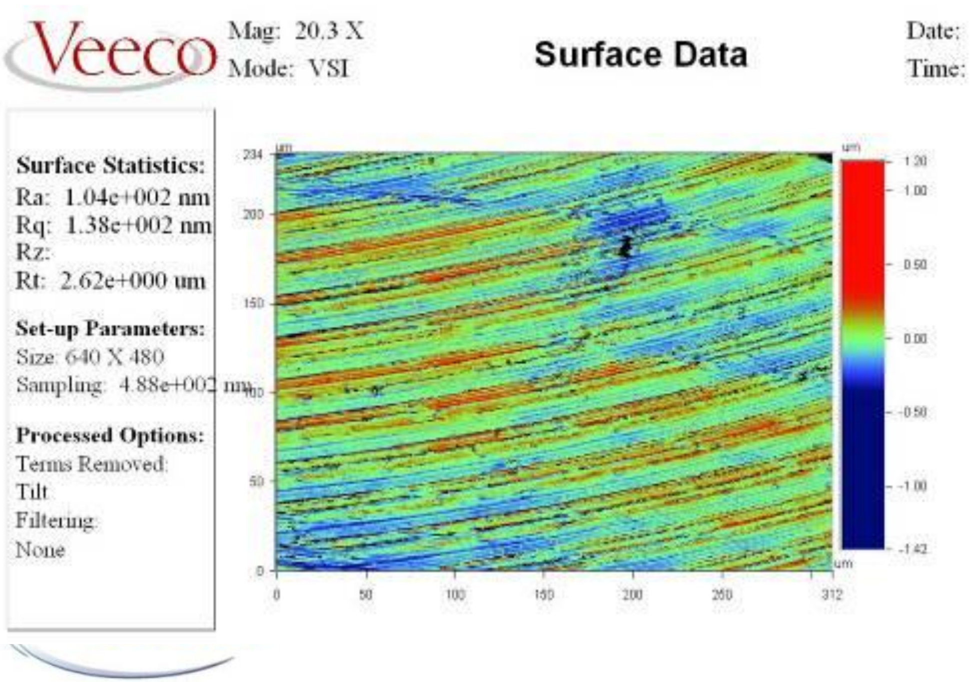


Prototype 1 – UK Built

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.

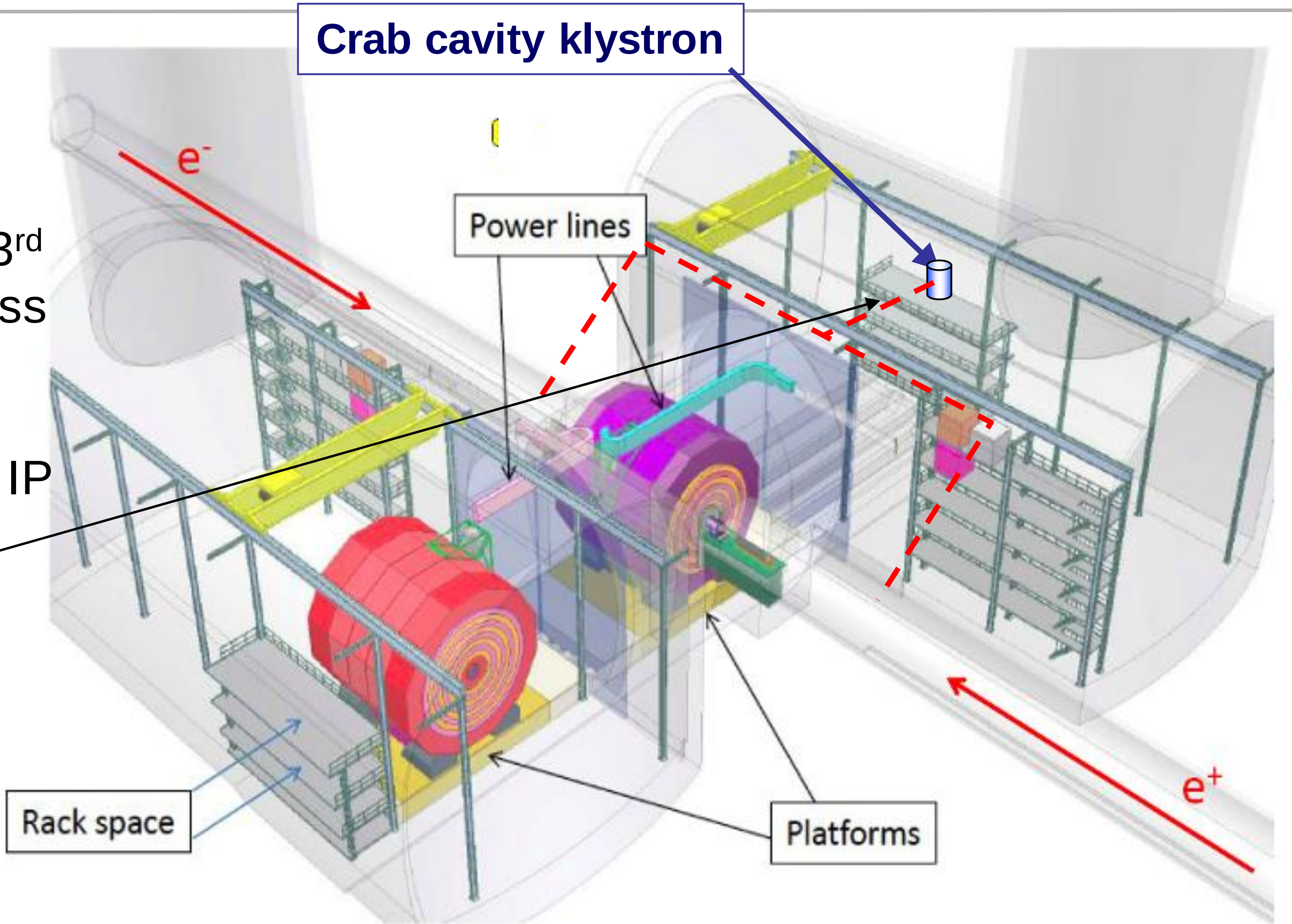
Waiting for flanges to be brazed.



CLIC detector halls

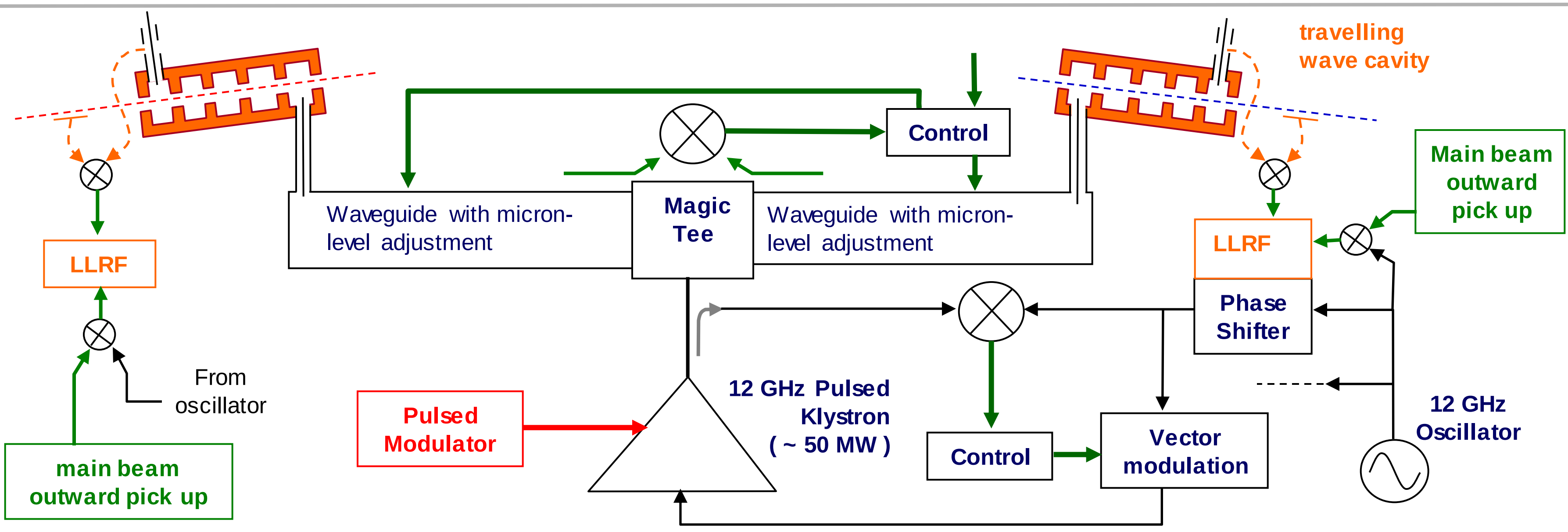
Have had meeting with MDI group (23rd Oct 2011) to discuss the location of the klystron and waveguides in the IP region.

Overmoded waveguide from magic tee to klystrons



~35m of waveguide from the Tee to the cavities

RF and sync to beam

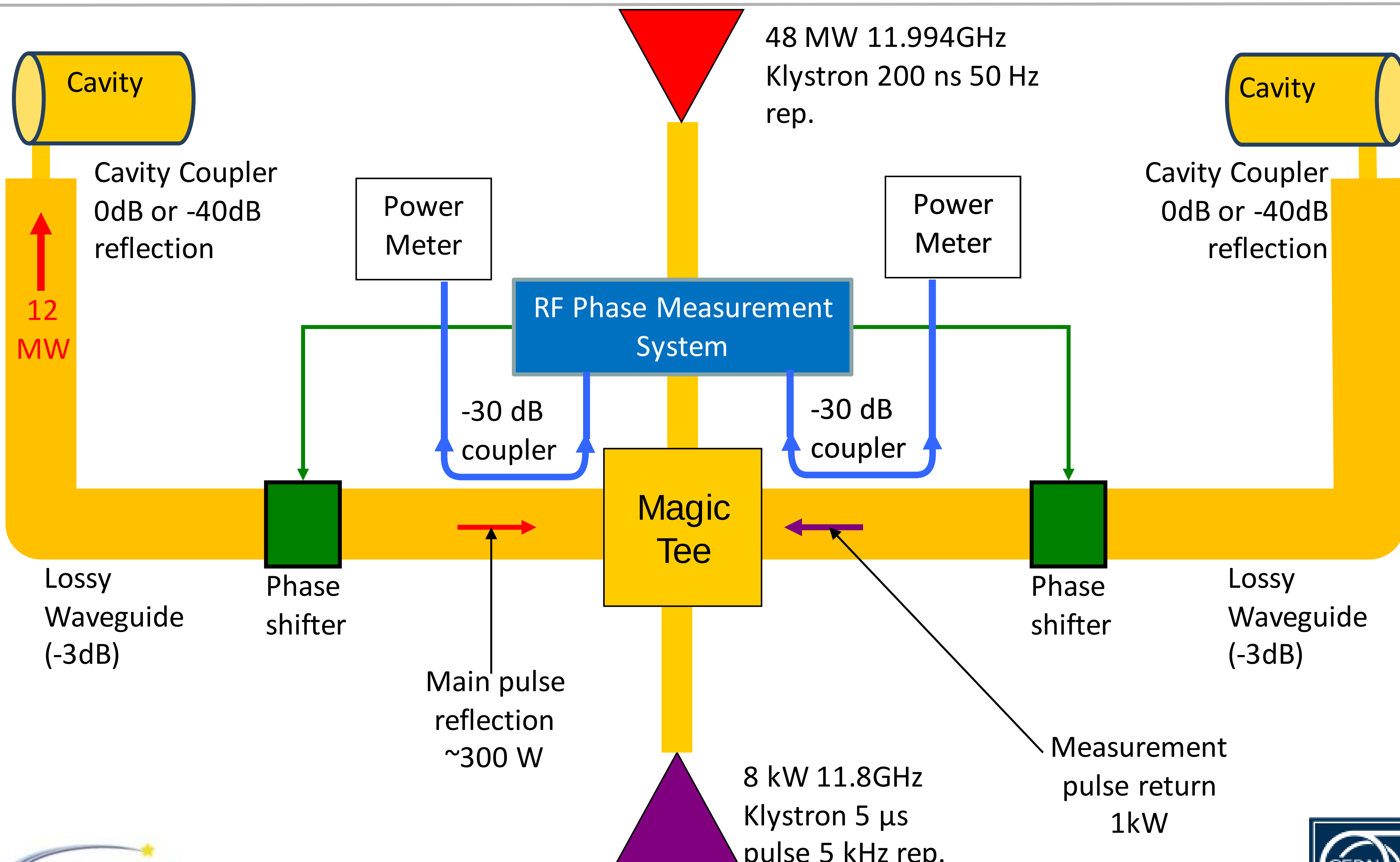


Estimate of bunch to RF synchronisation ~ 100 fs (0.43 degrees)

Once the main beam arrives at the crab cavity there is insufficient time to correct beam to cavity errors.

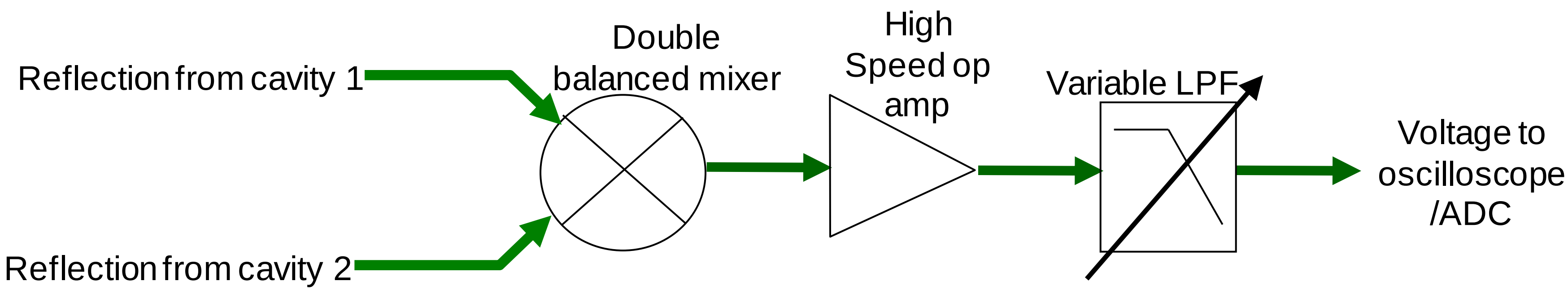
0. Send off frequency pre-pulse and measure phase difference of reflections
1. Perform waveguide length adjustment at micron scale
2. Measure phase difference between oscillator and outward going main beam
3. Adjust phase shifter in anticipation of round trip time and add offset for main beam departure 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

RF path length measurement



Phase measurement accuracy

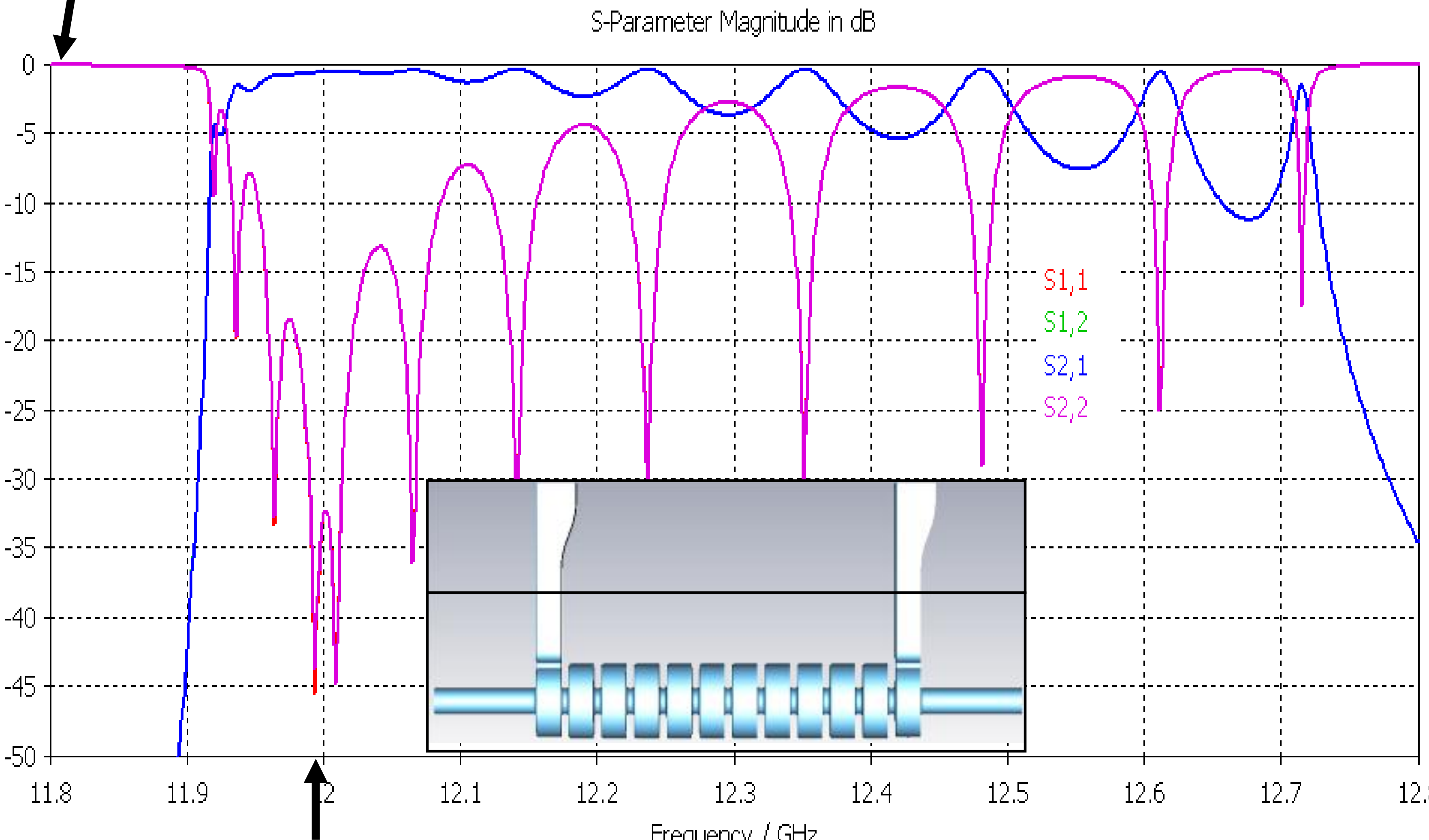
Accuracy depends on measurement bandwidth due to noise limitations (bandwidth determines minimum measurement time). Table below shows data for a single mixer + amplifier with 14 dBm power input: can use 4 to double accuracy and use more power.



Pulse length	Bandwidth	Thermal calculation (milli-deg)	RMS resolution measured (milli-deg)
0.14 ms	7 kHz	0.56	1.0
5 µs	200 kHz	3.0	4.6
33 ns	30MHz	37	57

Cavity reflection with frequency

Measurement pulse@11.8GHz, ≈100% reflection



Normal Operation @11.994 GHz, -45dB reflection

Waveguide choice

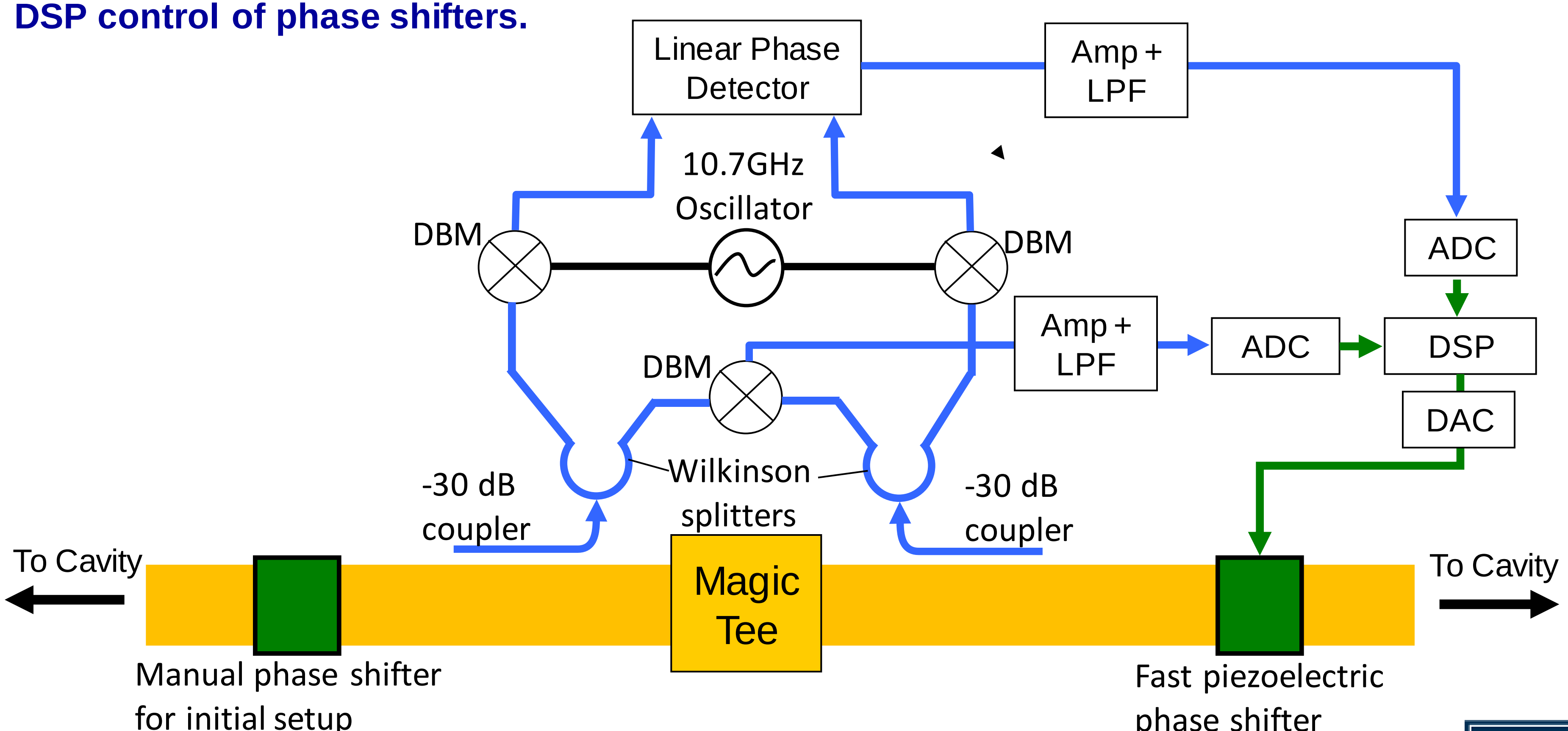
Waveguide type 35 meters COPPER Expansion = 17 ppm/K	Mode	Transmission	Timing error/0.3°C Width	Timing error/0.3°C length	Nº of modes
WR90(22.86x10.16mm)	TE10	45.4%	210.5 fs	498.9 fs	1
Large Rectangular (25x14.5mm)	TE10	57.9%	189.3 fs	507.8 fs	2
Cylindrical r =18mm	TE01	66.9%	804.9 fs	315.9 fs	7
Cylindrical r =25mm	TE01	90.4%	279.6 fs	471.4 fs	17

Copper coated extra pure INVAR 35 meters Expansion = 0.65 ppm/K	Mode	Transmission	Timing error/0.3°C Width	Timing error/0.3°C length	Nº of modes
WR90(22.86x10.16mm)	TE10	45.4%	8.13 fs	19.04 fs	1
Large Rectangular (25x14.5mm)	TE10	57.9%	6.57 fs	19.69 fs	2
Cylindrical r =18mm	TE01	66.9%	30.8 fs	12.1 fs	7
Cylindrical r =25mm	TE01	90.4%	10.7 fs	18.02 fs	17

Rectangular invar is the best choice as it offers much better temperature stability-> Expands 2.3 microns for 35 m of waveguide per 0.1 ℃.

LLRF Hardware Requirements

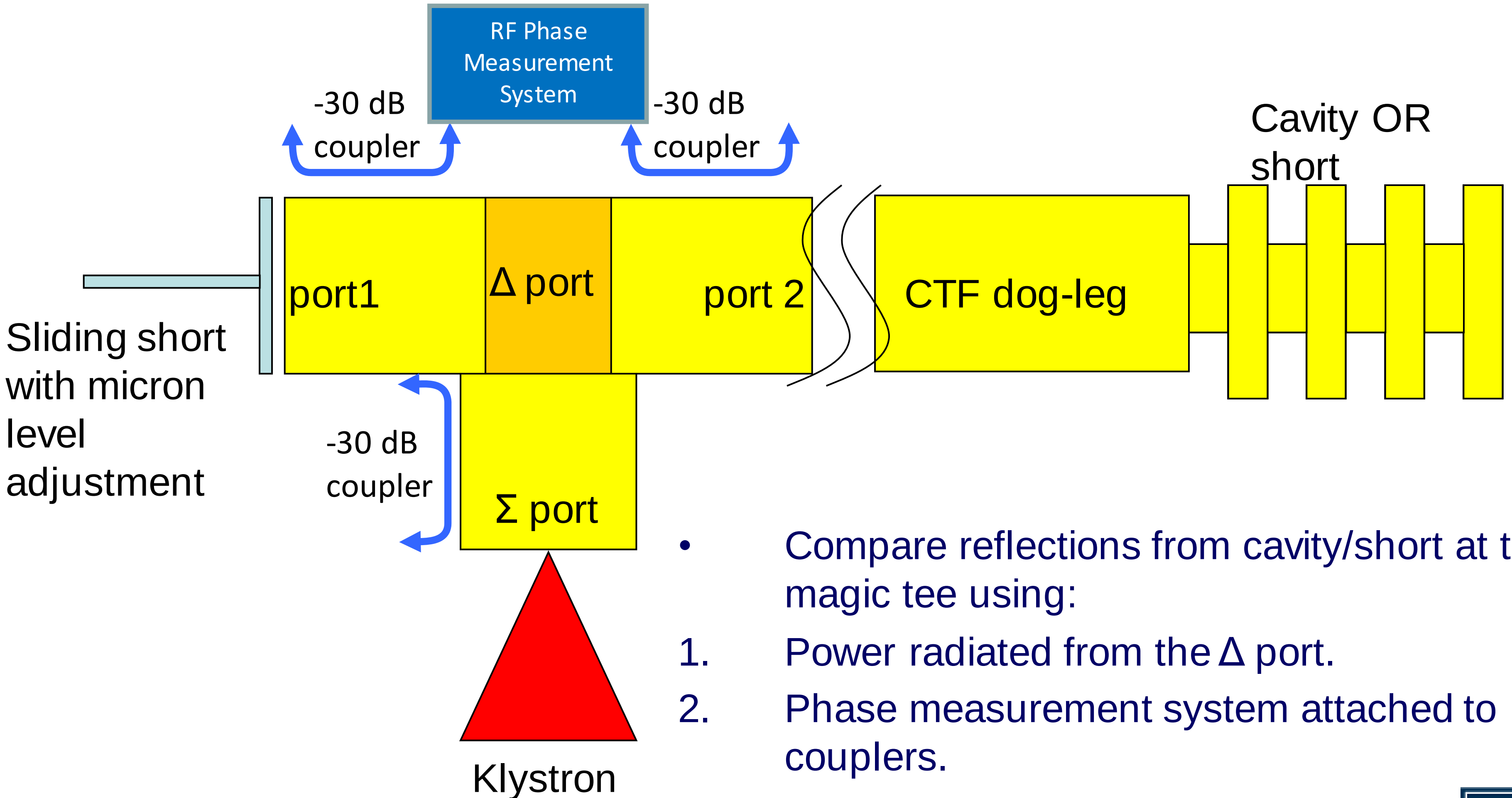
- **Fast phase measurements during the pulse (~20 ns).**
- **Full scale linear phase measurements to centre mixers and for calibration.**
- **High accuracy differential phase measurements of RF path length difference (5 μs, 5 kHz).**
- **DSP control of phase shifters.**



Prototype systems have been developed.

Proposed CTF dog-leg experiment

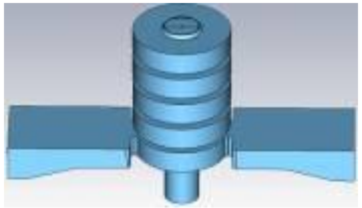
- Use klystron, slide tuner and magic tee to determine the phase stability of the CTF WG dog-leg.



- Compare reflections from cavity/short at the magic tee using:

1. Power radiated from the Δ port.
2. Phase measurement system attached to couplers.

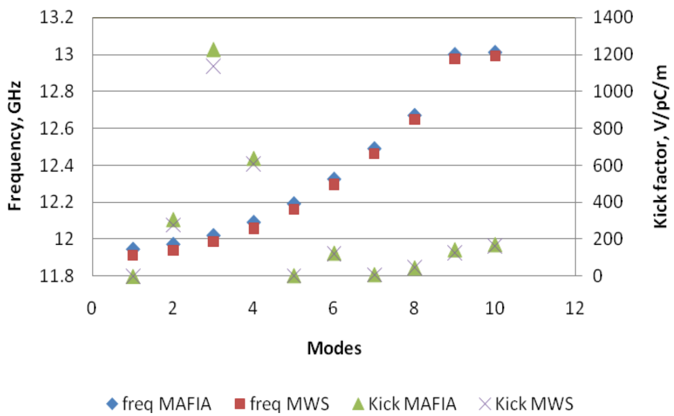
Wakefield calculations for cylindrical cavity

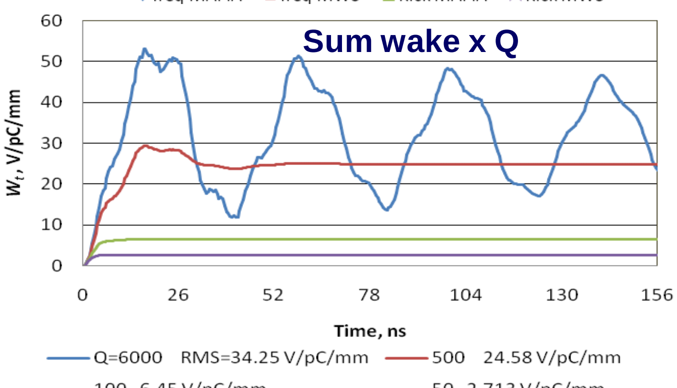


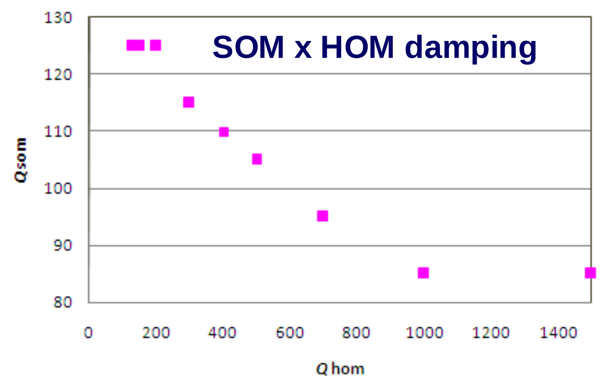
3D Eigen mode simulations were performed in Microwave studio for the first two vertical, horizontal and monopole pass-bands including input/output couplers.

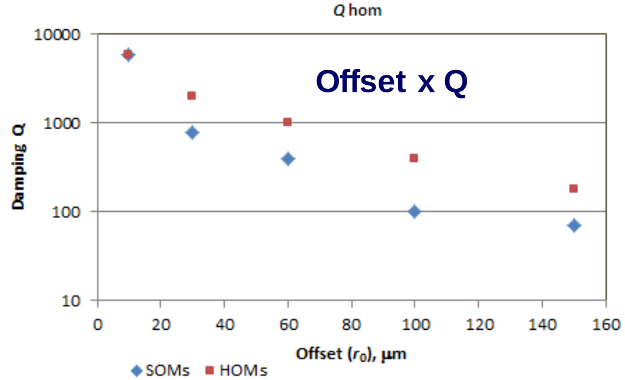
- The largest kick factor of any vertically polarised dipole mode is the $2\pi/3$ mode in the SOM pass band (k_t=1.2 V/pC/mm).
- The highest kick factor of a HOM is only 0.27 V/pC/mm. Three modes in the SOM pass band have higher kick factors.
- Hence the SOM pass band dominates the vertical wake.

SOM passband (freq and Kick factor)



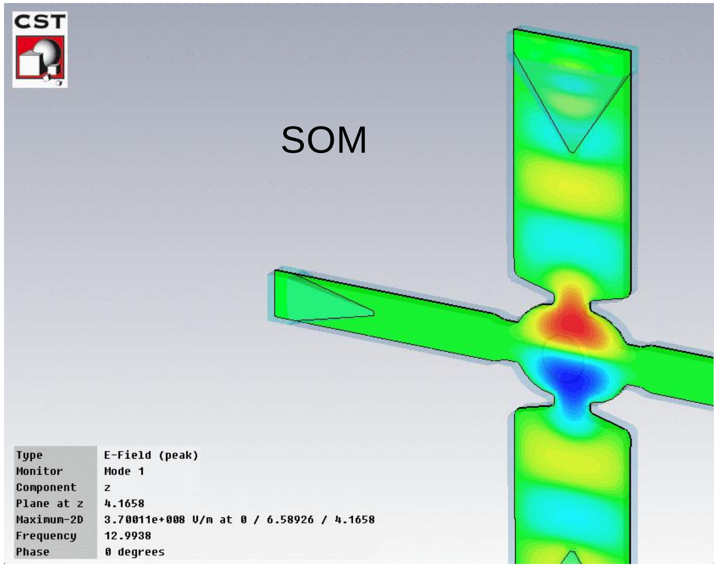


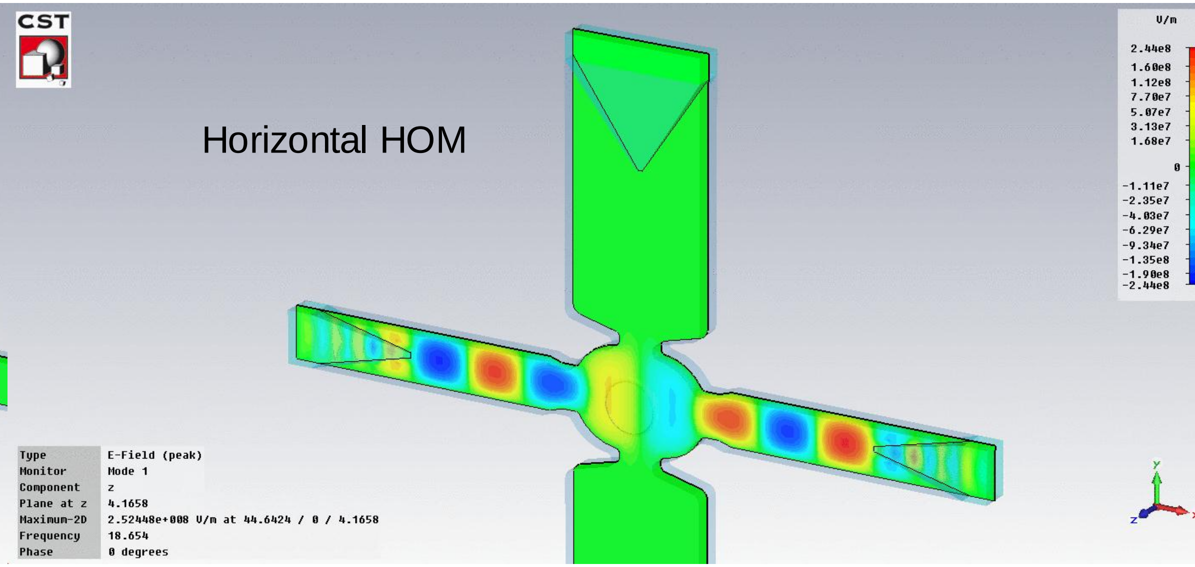


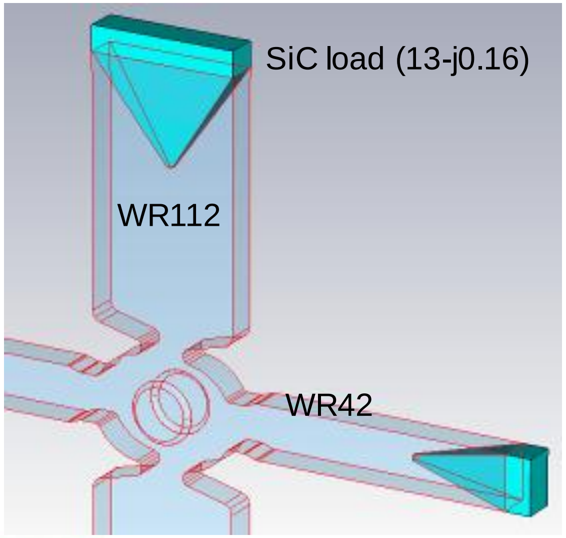


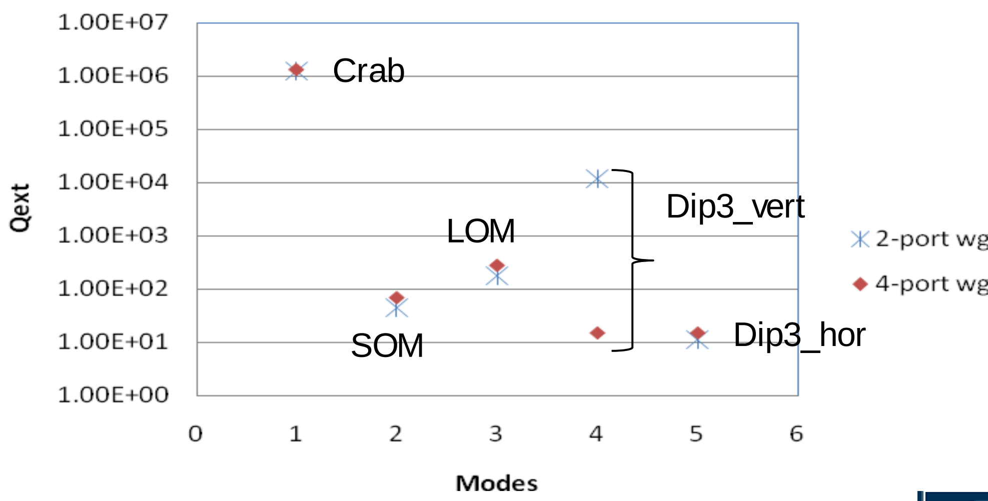
- Initially we worked on the assumption that all modes would be damped equally.
- This lead to a very stringent damping tolerance for a Q of 125.
- We assume a static offset of 35 microns (tolerance ~8.5 V/pC/mm).
- The required Q factors drop significantly as the static offset increases. If we assume a 0.1 mm offset we need to damp the SOM to a Q of 100.

Waveguide damping



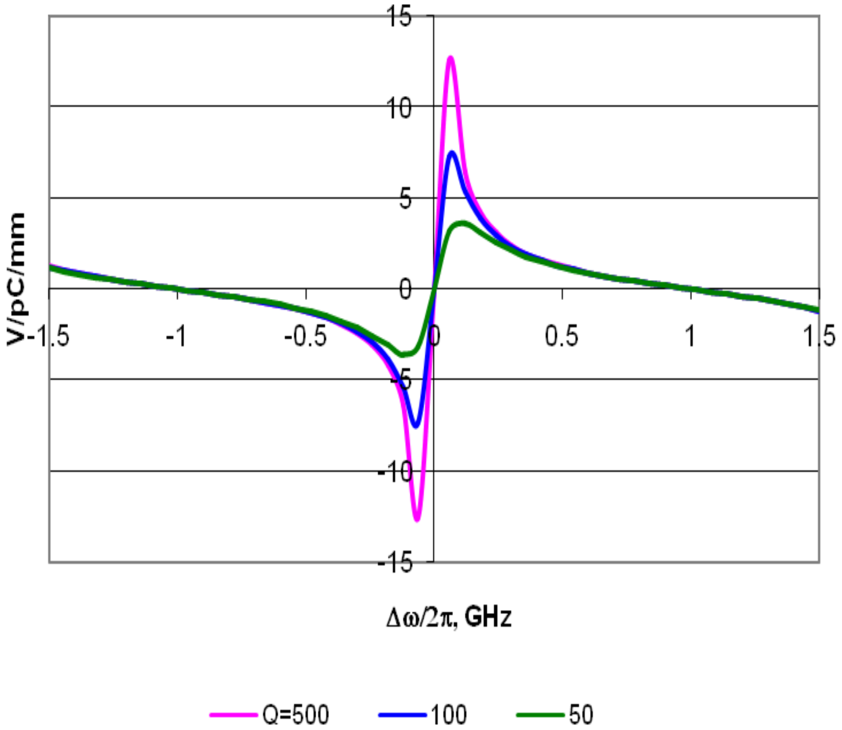






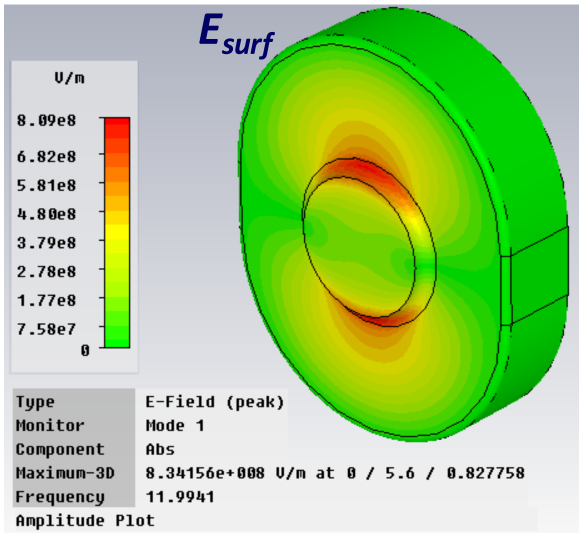
We can use a waveguide to damp the horizontal HOM's as well as long as the crab is below cut-off

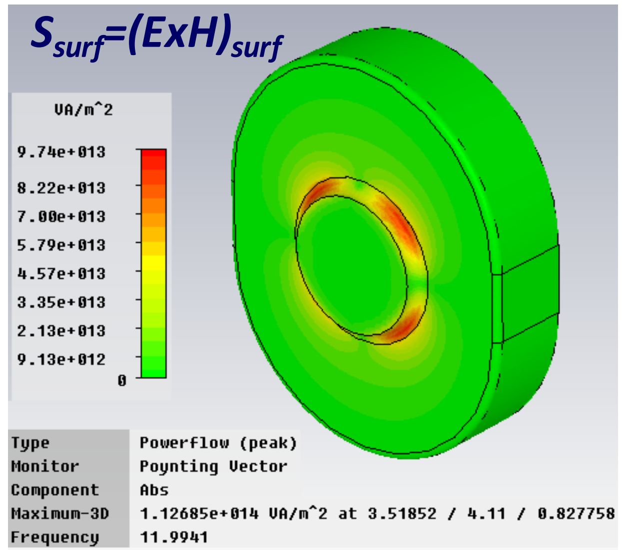
Single mode sum wakefield

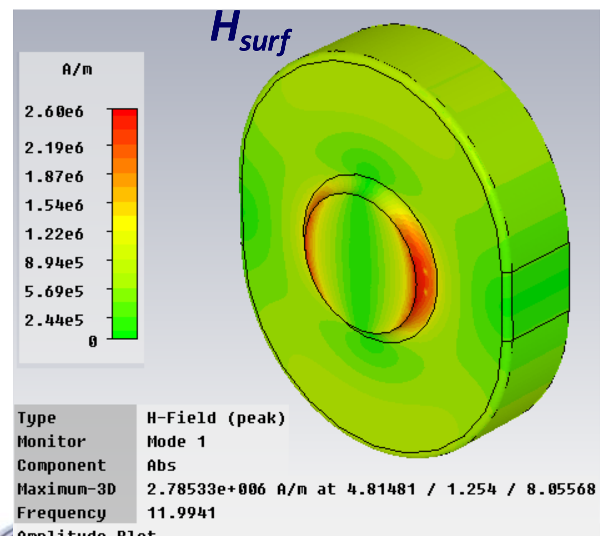


- If a single mode excitation by the beam is assumed, the sum transverse wakefield yields the function shown in the figure
- This is nearly true because the SOM dominates the vertical wakefield
- At Δf=0, the kick is zero but this point is close to the maximum wake as there is maximum energy in the cavity
- At +/- 1GHz, every bunch cancels the field induced by the previous bunch and wake is again zero
- This suggests the use of asymmetric cell shape to detune the SOM to 13 GHz
- At 13 GHz, all the modes in the pass band are far from resonance hence the required damping is reduced significantly from that of a symmetric cell shape

Racetrack cell-surface fields





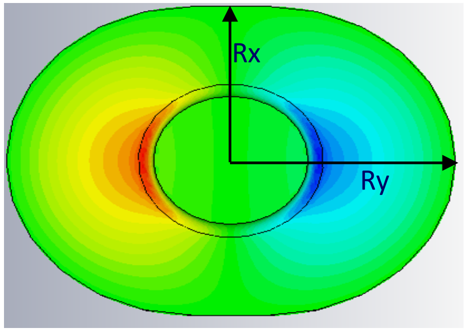


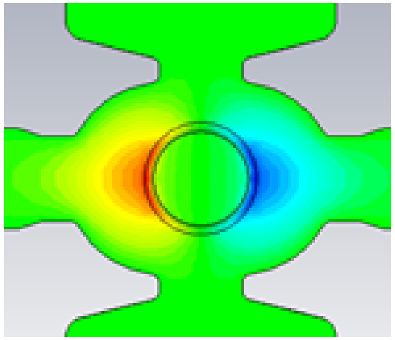
Property	Value
Energy stored, J	1
Q_{Cu}	6395
R_t/Q, Ohm	54.65
v_{gr}, %	-2.92
E_{surf}/E_t	3.43
H_{surf}/E_t	0.0114
Sc ($W/\mu m^2$)	3.32

- **Dipole fields are quite different from accelerating field**
- **Peak electric and magnetic fields of the dipole mode are located 90 degrees from each other on the iris**
- **Surface Poynting flux S_{surf} is however at 45 deg to both E and H**
- **Location of the breakdown on the iris provides critical information about the role of magnetic field in breakdown**
- **The cavity has a large Sc but relatively low E and H fields at the surface so this also provides an independent verification of new CERN theory.**

Undamped vs damped cell

Racetrack cell | **Waveguide damped**





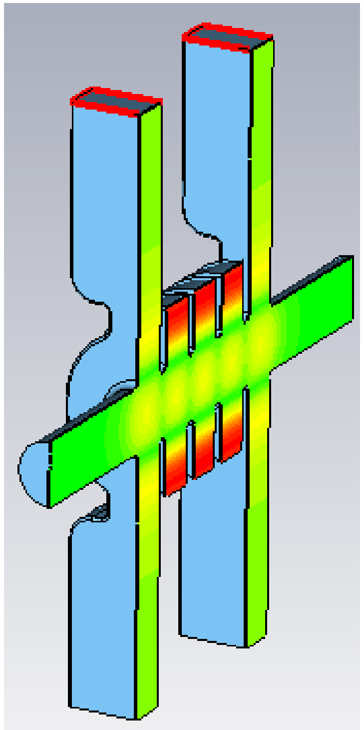
Ry/Rx=1.207, f_{crab}=12 GHz, f_{som}=13 GHz

Shape	Q	R_t/Q, Ohm	$-v_{gr}$, % c	E_m/E_t	H_m/E_t
Cylindrical-undamped	6396	53.66	2.94	3.497	0.0115
Racetrack-undamped	6395	54.65	2.93	3.425	0.0114
Racetrack-Damped	6022	50.57	2.63	3.676	0.0117

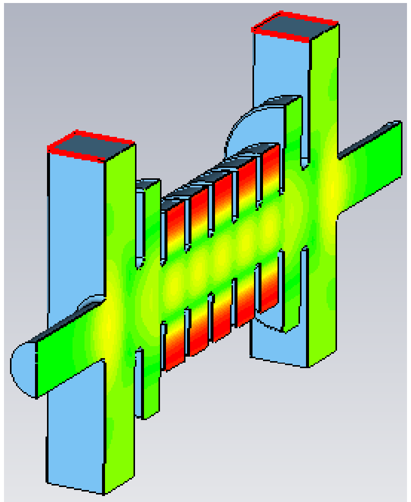
No major changes in RF properties with cell shape or damping

Coupler Options

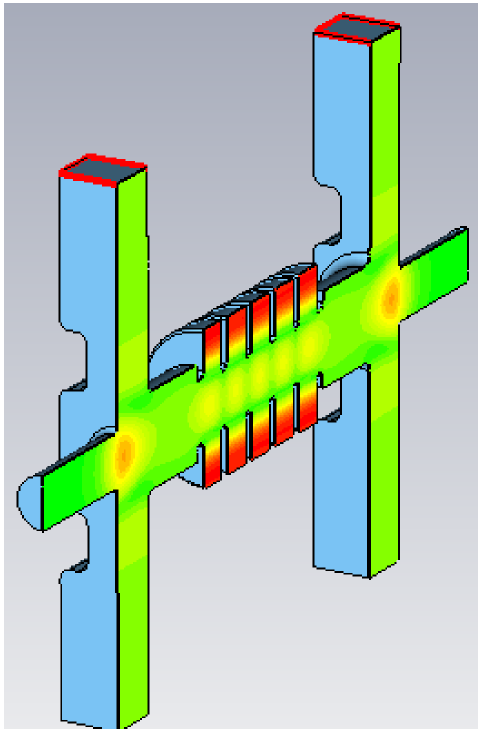
Standard



Waveguide

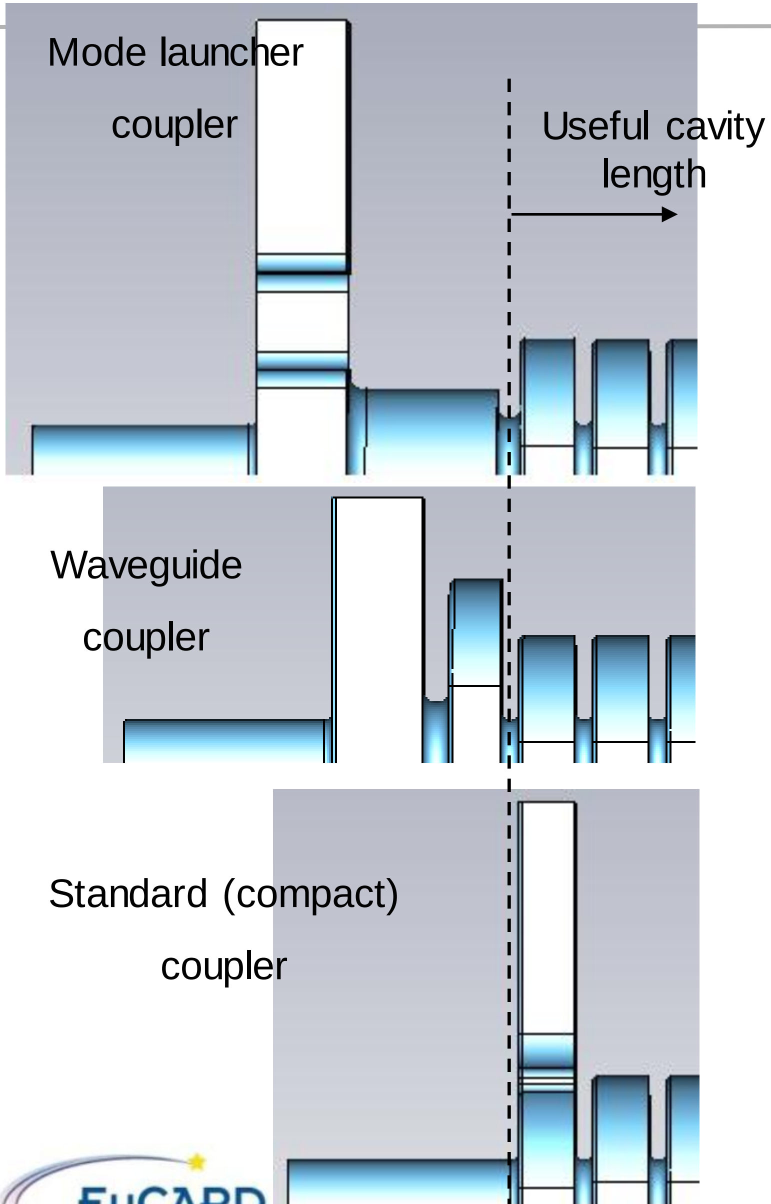


Mode launcher



We investigated Standard, Waveguide and Mode launch couplers

Coupler properties

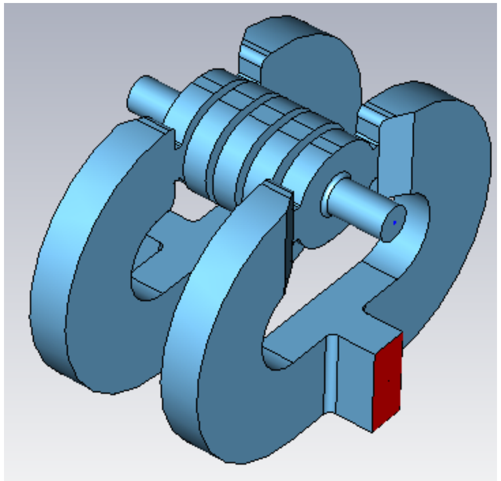


Surface fields for 12 cells, 2.55 MV kick

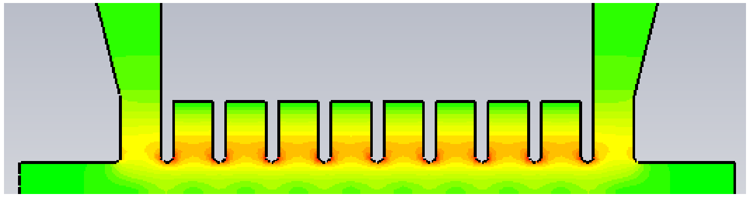
	E_{surf}, MV/m	H_{surf}, kA/m
Mode launcher	102	339
Waveguide	100	339
Standard	102	332

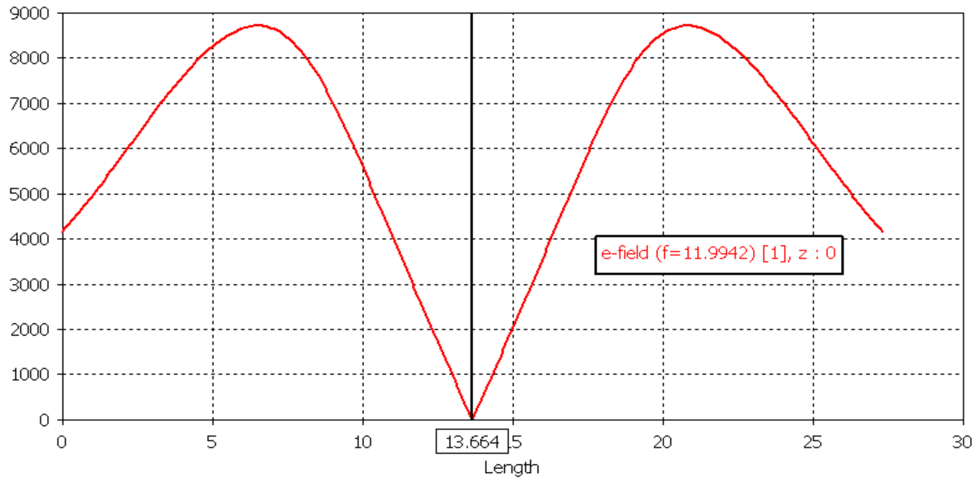
- **coupler type doesn't make a difference in the surface fields**
- **Because peak E and H fields lie on the irises for a dipole cavity**
- **So performance is not limited by the coupler heating**
- **We chose standard couplers for now as it is the most compact**

Dual feed coupler

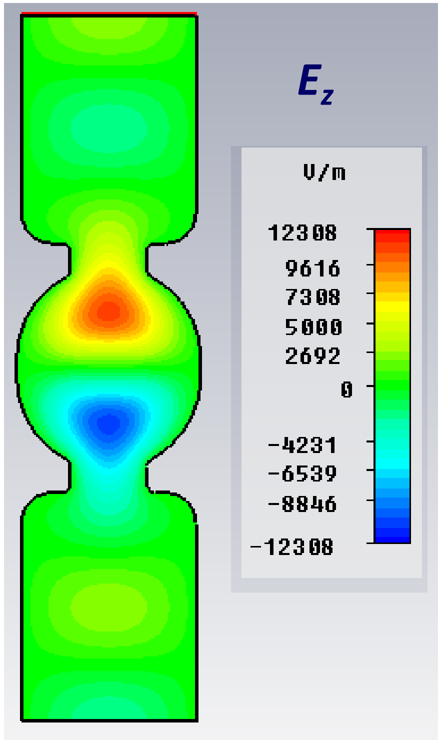


- Field has perfect symmetry about the coupler forcing the monopole component to essentially zero
- But needs two splitters which increases structure complexity and may have impact on phase stability
- Difficult to tune and damp end cell



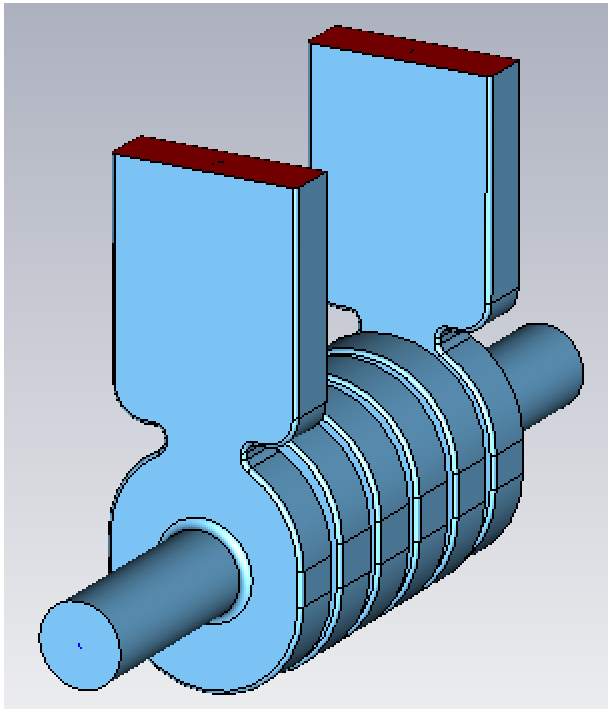


absE_z x y @ end cell

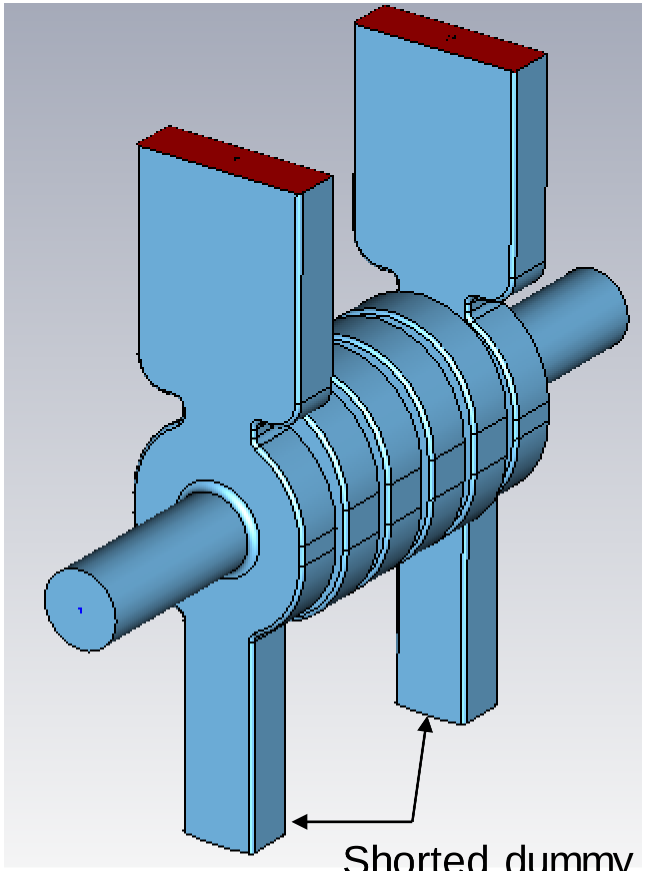


Single-feed coupler

(1) Standard single-feed



(2) Single-feed with dummy waveguide



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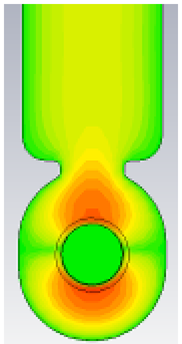
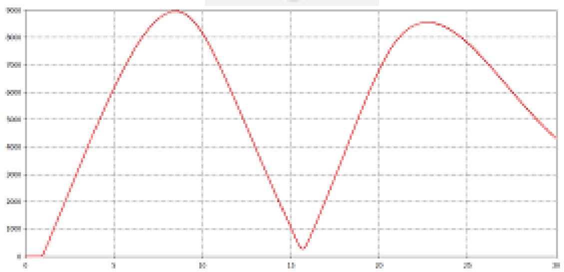
Single feed coupler

absEz x r in endcell for 1 W

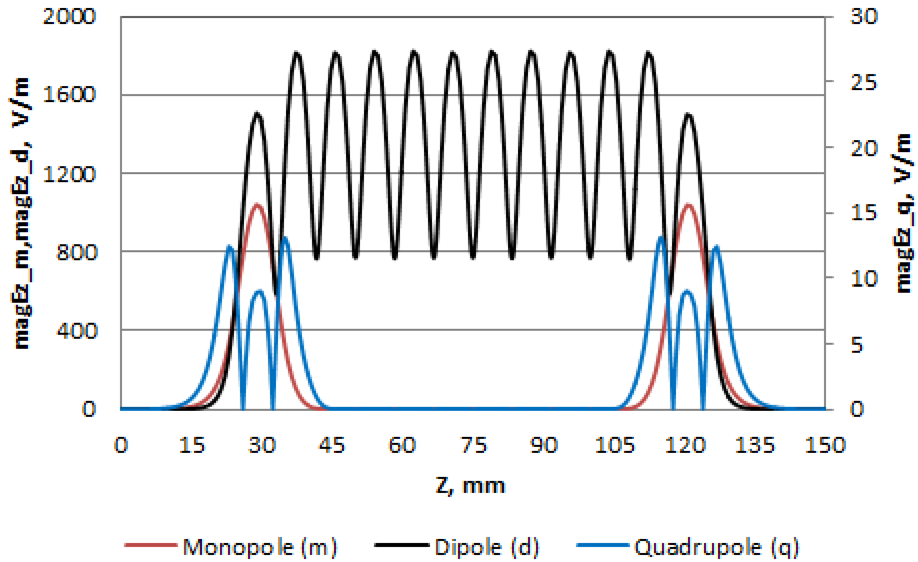
rad, mm





rad, mm

Multipole components

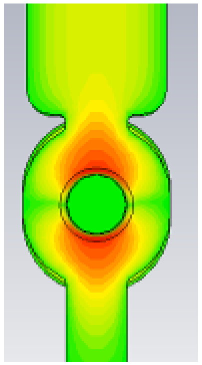


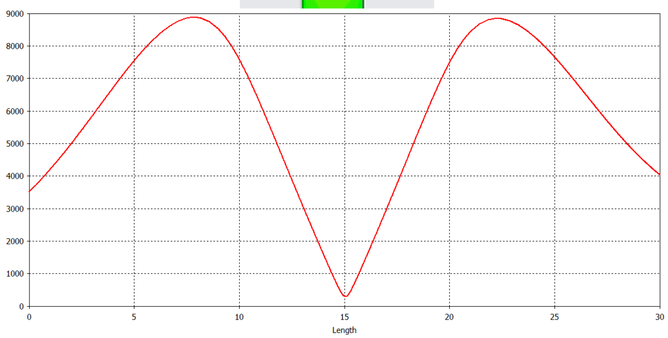
(on-axis) (1 mm off-axis) (1mm off-axis)

- **The coupler gives rise to a monopole (and higher order multipole) component in the endcells**
- **For 2.55 MV dipole kick, the corresponding monopole kick is 62 kV which is unwanted**
- **Rotating the couplers by 180 deg reduces the monopole kick to 8.7 kV but doesn't cancel, as this component is out of phase with the dipole**
- **Small adjustment of the endcell length adjusts the beam phase which reduces the monopole kick to a few tens of volts**

With dummy waveguide

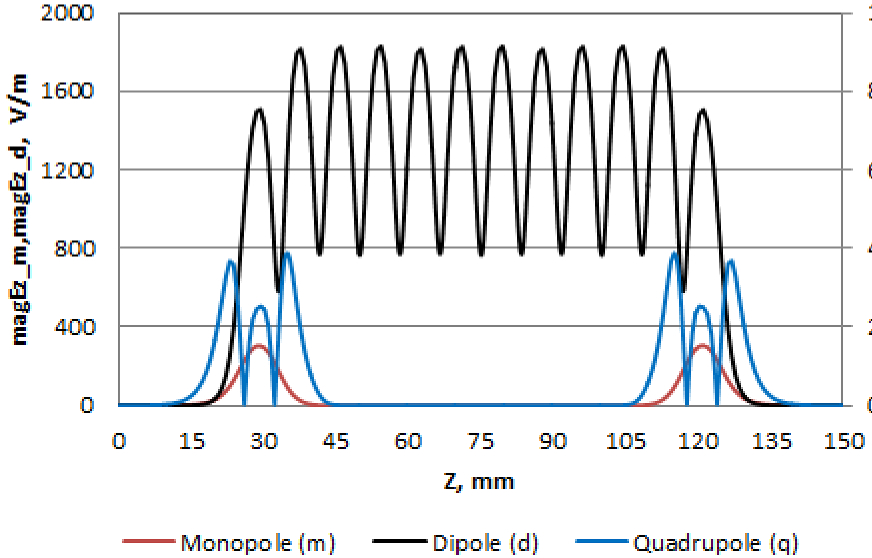
absEz x r in endcell for 1 W





rad, mm ⟶

Multipole components

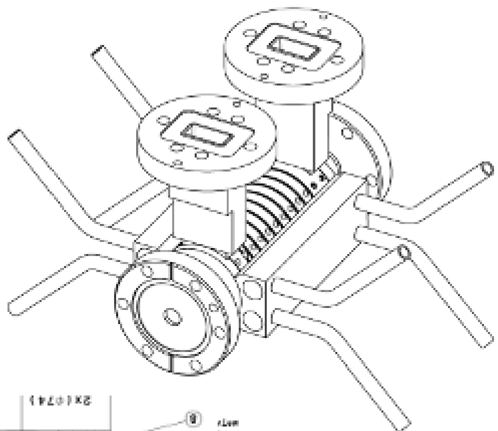


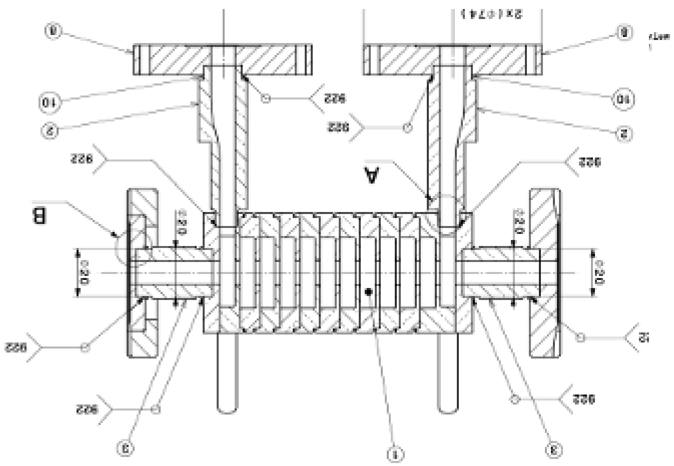
(on-axis) **(1 mm off-axis)** **(1mm off-axis)**

- **Dummy waveguide reduce the monopole component in the end cells by about 3 times**
- **The dummy guide width can be fine adjusted for phase adjustment of the monopole to reduce the kick voltage to a few 10s of volts**
- **As the present prototype doesn't see a beam, we chose not to use the dummy guide**

Parameters for un-damped prototype

Drawings done at CERN and manufacture is progressing at VDL





Number of cells	12
Total length (mm)	149.984
Active length (mm)	99.984
Vertical size (mm)	59.354

Mode (rad, GHz)	$2\pi/3$, 11.9942
$\lvert S_{11}\rvert$ (dB)	−45.00
$\lvert S_{21}\rvert$ (dB)	−0.61
Q_{Cu}	6247
Group vel, %c	−2.90
Fill time, ns	11.50
Attenuation, Nep/m	0.69
Kick (MV)	2.56
Peak power (MW)	13.35
E_{surf} (MV/m)	103
H_{surf} (kA/m)	348 (regular cell), 207 (coupler slot)
ΔT (K)	26 (regular cell), 10 (coupler slot)
S_c (W/μm^2)	3.32

Cavity tuning

The Cockcroft Institute of Accelerator Science and Technology

LANCASTER UNIVERSITY

- **Pins attached at 45 deg to the racetrack cell will help frequency tuning**
- **Field measurement using bead pull followed by non-resonant perturbation technique will help matching the structure in a few iterations**

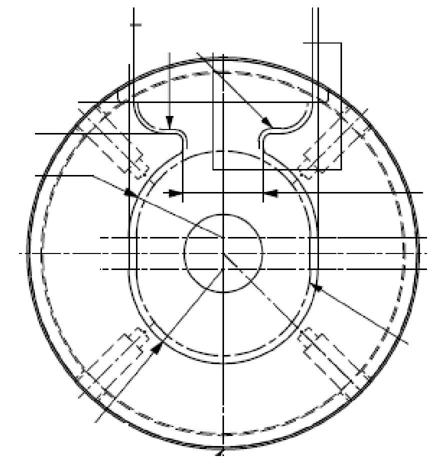
$$\Delta S_{11}=S_{11}^{p}-S_{11}^{u} = -j\omega kF^2/2P_{in}$$

P_{in}=input power

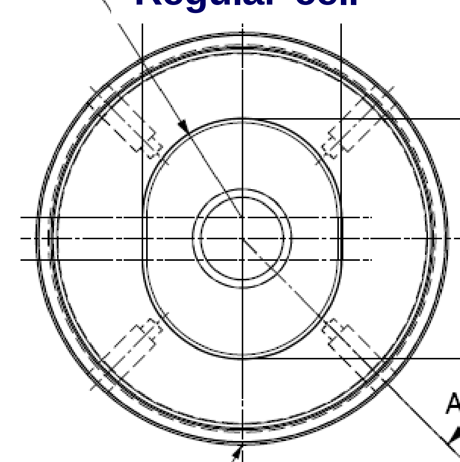
$S_{11}^{p/u}$=perturbed/unperturbed complex reflection coefficient at input coupler

F=Field quantity perturbed by the bead

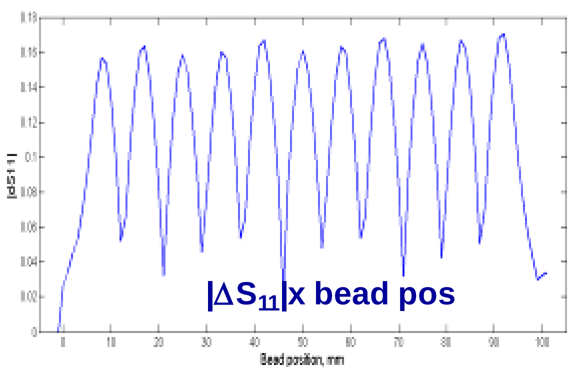
Endcell



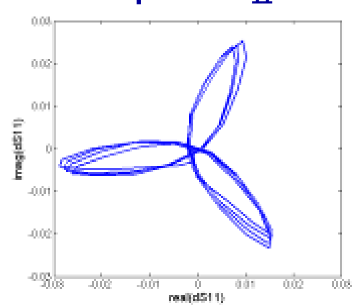
Regular cell



Beadpull simulation with metallic disk, 1.5 mm dia, 0.5 mm thickness



Complex ΔS_{11}



- T.Khabiboulline, A new tuning method for travelling wave structures, PAC95
- J. Shi et.al, Tuning of CLIC accelerating structure prototypes at CERN, LINAC10

EuCARD

CERN

Summary

Cavity development/testing

- Awaiting gradient tests of a cell design excited in a dipole mode at SLAC.
- Ongoing manufacture of a multi-cell un-damped cavity for high power tests at CERN.
- Ongoing design of a multi-cell damped cavity.

RF distribution system development

- Ongoing design/manufacturing of measurement sampling electronics.
- Experiments to understand stability of the RF distribution system presented.
- R&D as necessary to improve stability of RF distribution system presented.