CLIC Crab Cavities

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(on behalf of the LC Crab System Collaborations)

CERN

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Crab cavity development for CLIC

Contributors

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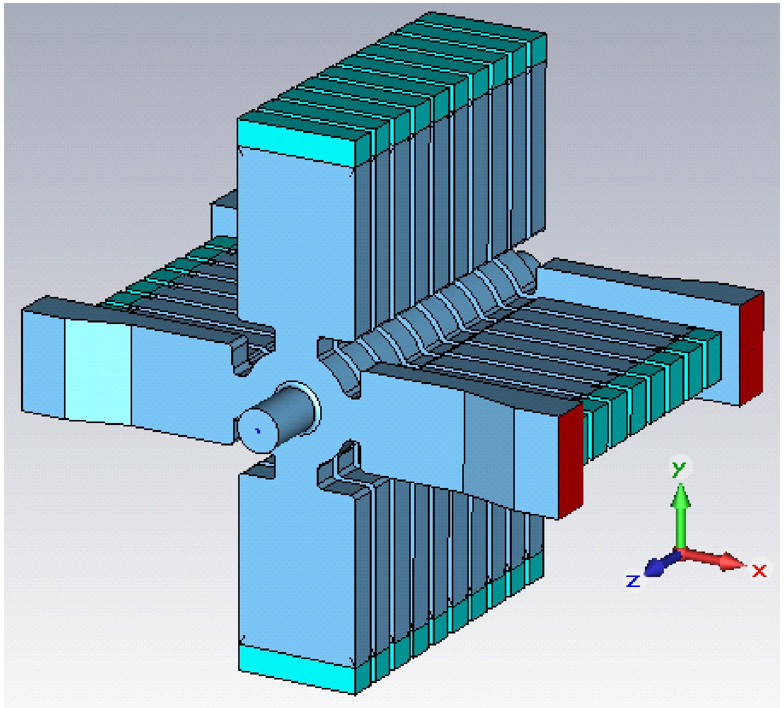
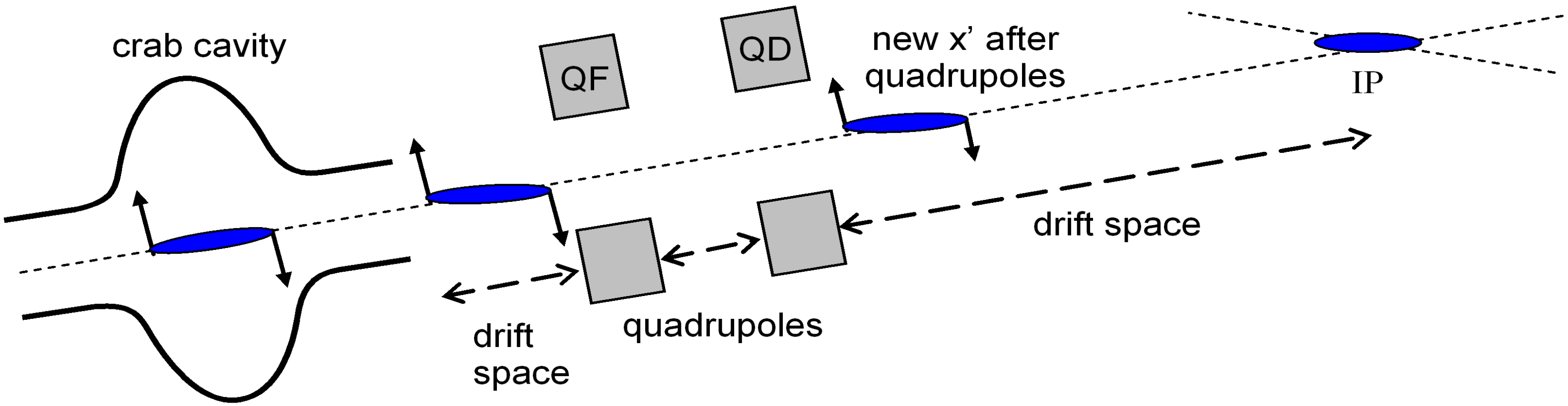
Manchester University	Roger Jones
SLAC	Sami Tantawi

Since Last Year



- Input coupler design
- Cell number optimisation
- Revised wakefield calculations
- Structure design with waveguide damping
- PLACET simulations of crabbed verses un-crabbed verses head on
- Phase measurement hardware development

Crab Cavity Function



The crab cavity is a deflection cavity operated with a 90º phase shift.

A particle at the centre of the bunch gets no transverse momentum kick and hence no deflection at the IP.

A particle at the front gets a transverse momentum that is equal and opposite to a particle at the back.

The quadrupoles change the rate of rotation of the bunch.

Crab Cavity Issues

- Wakefields - cause kicks and emittance growth
- Poor Phase Stability - gives large horizontal kicks
- Beam-loading - has large unpredictable fluctuations on a time scale of tens of ns

Key Required Outcomes

- Damp, measure and confirm the predicted wakes.
- Establish feasible/achievable level of phase control performance. (Requirement looks beyond state of the art)
- Need solution which is insensitive to beam-loading

Solution

Wakefields	Large irises Small number of cells Strong damping
Phase and amplitude control	Passive during 156 ns bunch train
Beamloading compensation	High energy flow through cavity * *small number of cells* * *high group velocity* * *low efficiency*
Phase synchronisation	Same klystron drives both cavities Temperature stabilized waveguide
Phase reference	Optical interferometer
Phase measurement	Down conversion to ~ 1 GHz, Digital phase detection Staggered sample and hold
Phase stability	Thick irises Strong cavity cooling

CLIC and ILC Parameters

- CLIC bunches ~ 45 nm horizontal by 1 nm vertical size at IP.
- ILC bunches ~ 600 nm horizontal by 4 nm vertical size at IP.

Beamloading with offset (a)

$$P_b = \frac{a\ \theta_c\ q\ f_{rep}\ E_o}{2 R_{12}}$$

	Max bunch offset (a)	crossing angle θ_c	bunch charge (q)	bunch repetition	Beam energy E_o	R12	Crab peak power
ILC	0.6 mm	0.014 rad	3.2 nC	3.03 MHz	0.5 TeV	16.4 m rad^{-1}	1.24 kW
CLIC	0.4 mm	0.020 rad	0.6 nC	2.00 GHz	1.5 TeV	25.0 m rad^{-1}	288 kW

Cavity to Cavity Phase synchronisation requirement

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

	Luminosity fraction S	f (GHz)	σ_x (nm)	θ_c (rads)	ϕ_{rms} (deg)	Δt (fs)	Pulse Length (μs)
CLIC	0.98	12.0	45	0.020	0.0188	4.4	0.14
CLIC (4 GHz)	0.98	4.0	45	0.020	0.0063	4.4	0.14
ILC	0.98	3.9	655	0.014	0.1271	90.5	1000.00

Kick and tolerance for 3 TeV CM

To minimise required cavity kick R12 needs to be large (25 metres suggested)
Vertical kicks from unwanted cavity modes are bad one need R34 to be small.
For 20 mrad crossing and using as 12 GHz structure

$$V_{crab} = \frac{\theta_r E_o c}{R_{12}\omega} = \frac{10^{-2} \times 1.5 \times 10^{12} \times 3 \times 10^{8}}{25 \times 2\pi \times 12 \times 10^{12}} = 2.4\,\mathrm{MV}$$

Error in kick gives tilts effective collision from head on.

Luminosity Reduction Factor $S \approx \dfrac{1}{\sqrt{1 + \left\{ \dfrac{\sigma_z \theta_c}{4\sigma_x} \dfrac{\left(|\delta V_1| + |\delta V_2|\right)}{V_{crab}} \right\}^2}}$ gives

amplitude error on each cavity	1.0%	1.5%	2.0%	2.5%	3.0%
luminosity reduction	0.9953	0.9914	0.9814	0.9714	0.9596

Cell number optimisation

Un-damped case – Maximum surface field = 110 MV m^{-1} (Offset 400 μm)

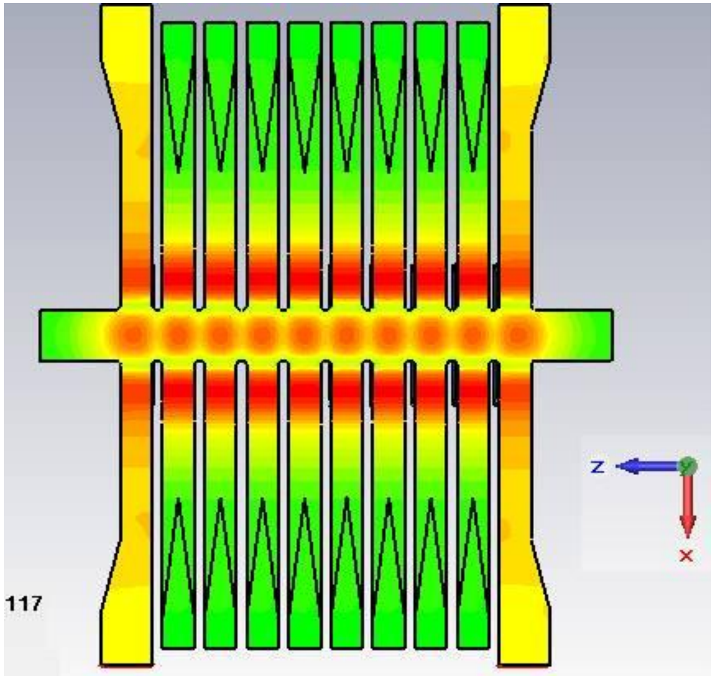
iris radius (mm)	R/Q transverse	Q	group vel % of c	E_{surf}/E_{trans}	Minimum cells	Power MW	Amplitude error
4.0	66.637	6638	-2.880	2.723	8	19.3	0.34%
4.5	61.162	6496	-3.230	3.031	9	18.7	0.35%
5.0	53.922	6371	-2.931	3.566	10	15.7	0.43%
6.0	38.619	6274	0.140	4.404	no	solution	
6.5	31.817	6285	2.870	5.087	14	13.7	0.51%
7.0	25.517	6498	6.243	5.630	16	27.3	0.25%

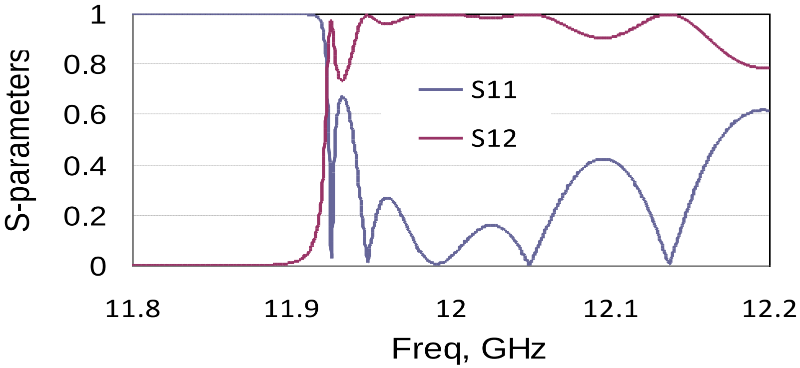
Un-damped case – Maximum surface field = 70 MV m^{-1} (Offset 400 μm)

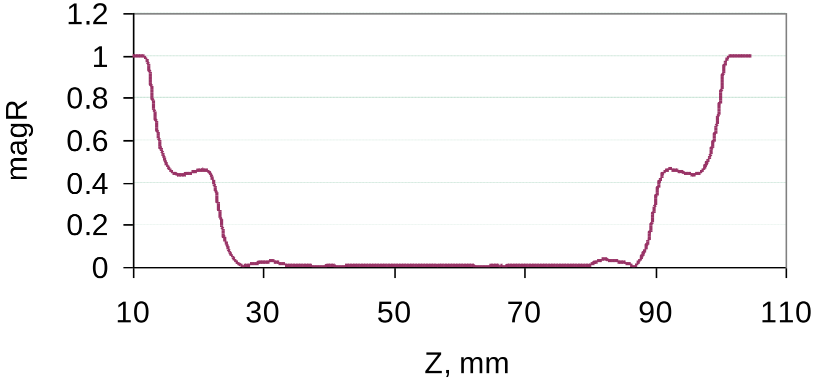
iris radius (mm)	R/Q transverse	Q	group vel % of c	E_{surf}/E_{trans}	Minimum cells	Power MW	Amplitude error
4.0	66.637	6638	-2.880	2.723	12	8.8	0.77%
4.5	61.162	6496	-3.230	3.031	13	9.1	0.76%
5.0	53.922	6371	-2.931	3.566	16	6.6	1.12%
6.0	38.619	6274	0.140	4.404	no	solution	
6.5	31.817	6285	2.870	5.087	23	5.3	1.40%
7.0	25.517	6498	6.243	5.630	24	12.4	0.53%

Damped cavity

Transverse Magnetic Field







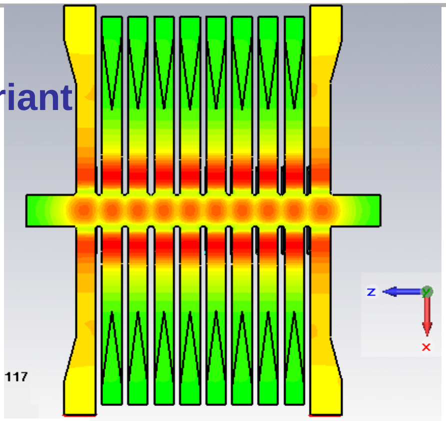
Damped case – Maximum surface field = 110 MV m^{-1} **(Offset 400 μm)**

iris radius (mm)	R/Q transverse	Q	group vel % of c	E_{surf}/E_{trans}	Minimum cells	Power MW	Amplitude error
5.0	52.868	5964	-2.631	3.552	10	14.53	0.47%

Needs a bit less power than the un-damped but has marginally bigger amplitude error

Application of Floquet theorem for TW match

- Cut-off waveguides couple to the end cells
- Couplers are symmetric waveguides keeping end cell electrical centre invariant
- Power needs to be split equally and fed to the couplers



An ideally matched TW cavity should have,

(1) Zero reflection at the couplers (external matching)

(2) Zero internal reflection along z (symmetric and flat field)

(3) Constant phase advance per cell along z (120^o)

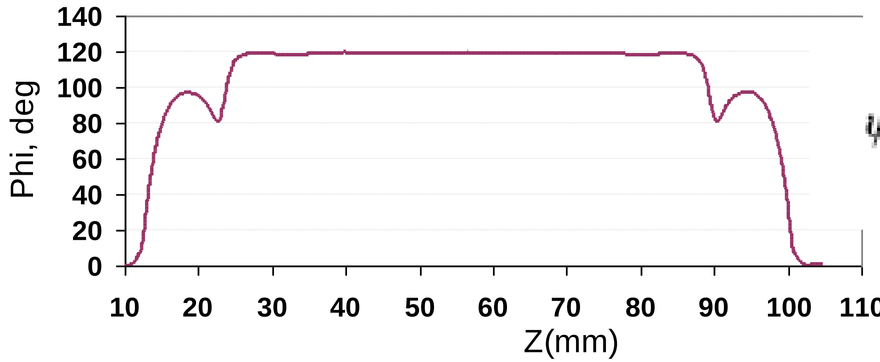
Compute Δ and Σ using

$$\Delta(z) = \frac{E(z+P) - E(z-P)}{E(z)}$$

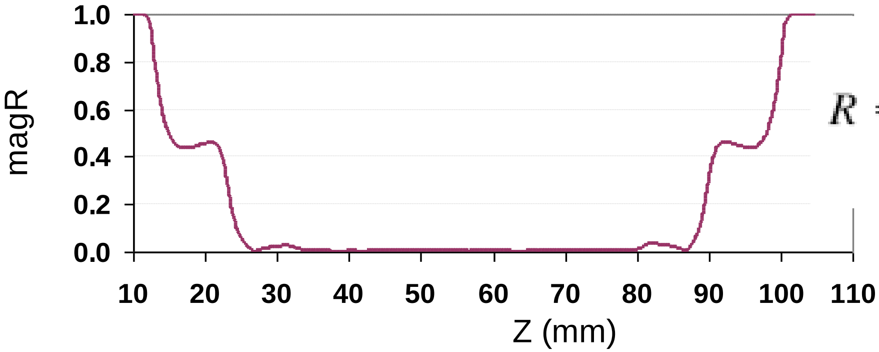
$$\Sigma(z) = \frac{E(z+P) + E(z-P)}{E(z)}$$

(P = period)

Then determine reflected amplitude and phase



$$\psi = \cos^{-1}\frac{\Sigma(z)}{2}$$



$$R = \frac{2\sin\psi - i\Delta(z)}{2\sin\psi + i\Delta(z)}.$$

Waveguide choice

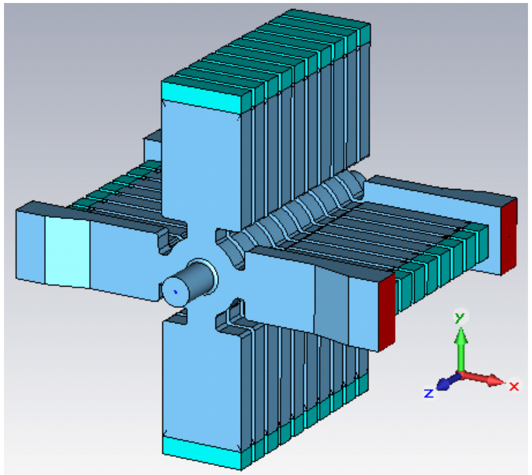
Assume 50 m waveguide run from Klystron to each Crab cavity

For copper s =5.8e7 S/m and at 11.994 GHz	Attenuation	Transmission	Over moded
Rectangular TE10 EIA90 (22.9 x 10.2 mm)	0.098 dB/m	32.4%	no
Rectangular TE10 special (24 x 14 mm)	0.073 dB/m	43.4%	no
Circular TE11 (r = 9.3 mm)	0.119 dB/m	25.3%	no
Circular TE11 (r = 12 mm)	0.055 dB/m	53.2%	TM10
Circular TE01 (r = 40 mm)	0.010 dB/m	89.1%	extremely

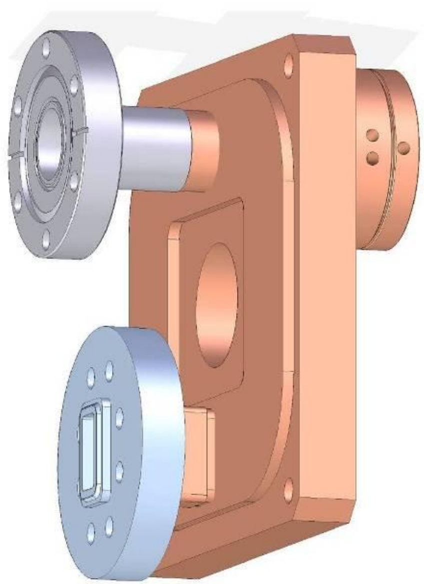
Available klystron has nominal output of 70 MW so run at 60 MW
Divide output for two beam lines = 30 MW
For standard rectangular waveguide we have 9.7 MW available **(OK for 16 cells)**
For special rectangular waveguide we have 13.0 MW available
For circular 12mm TE11 waveguide we have 15.9 MW available **(OK for 10 cells)**

(note that mode conversion from circular TE11 to circular TM10 is vanishingly small for properly designed bends)

Joining the coupler ends



Efficiency and minimisation of mode conversion and reflection in the RF distribution will be critical. One task for which good designs already exist is combining the two cavity input ports compactly.



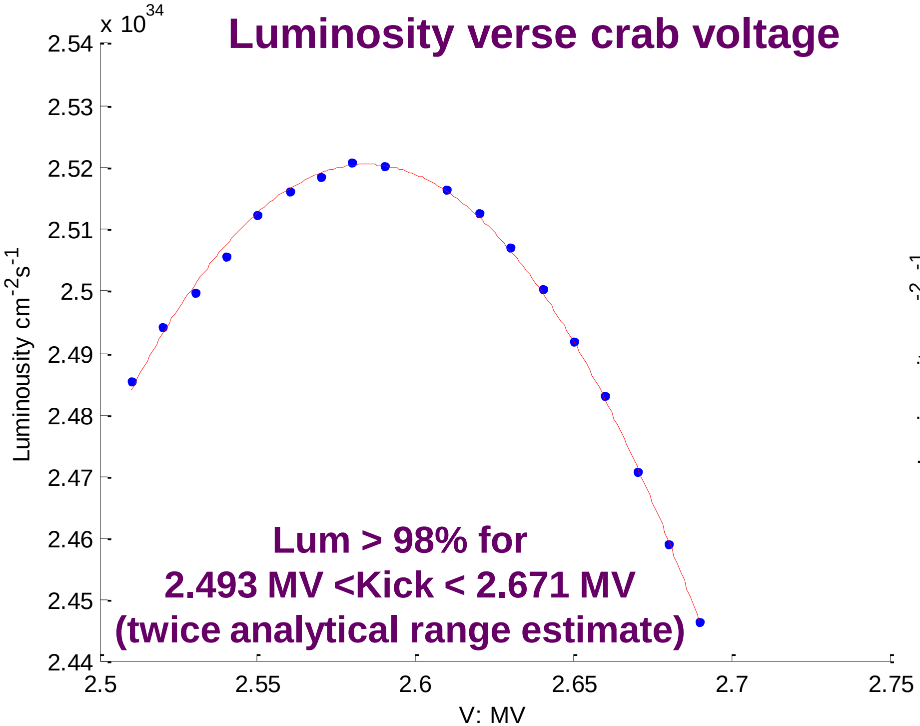
Mechanical Design Model

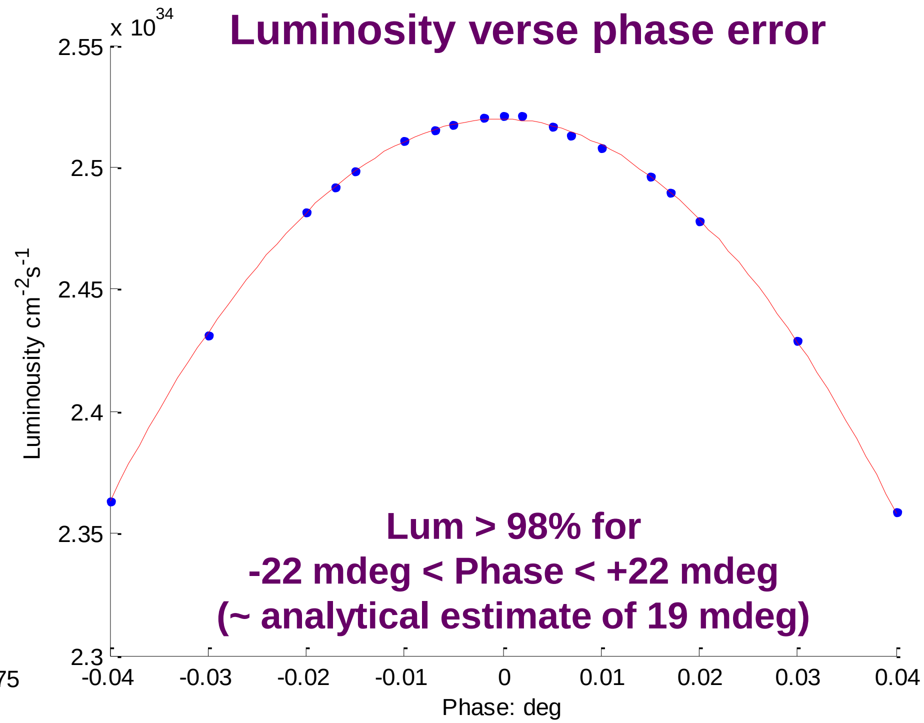
Completed Coupler Assembly

J. Wang et al., SLAC

Results from PLACET + Guinea Pig

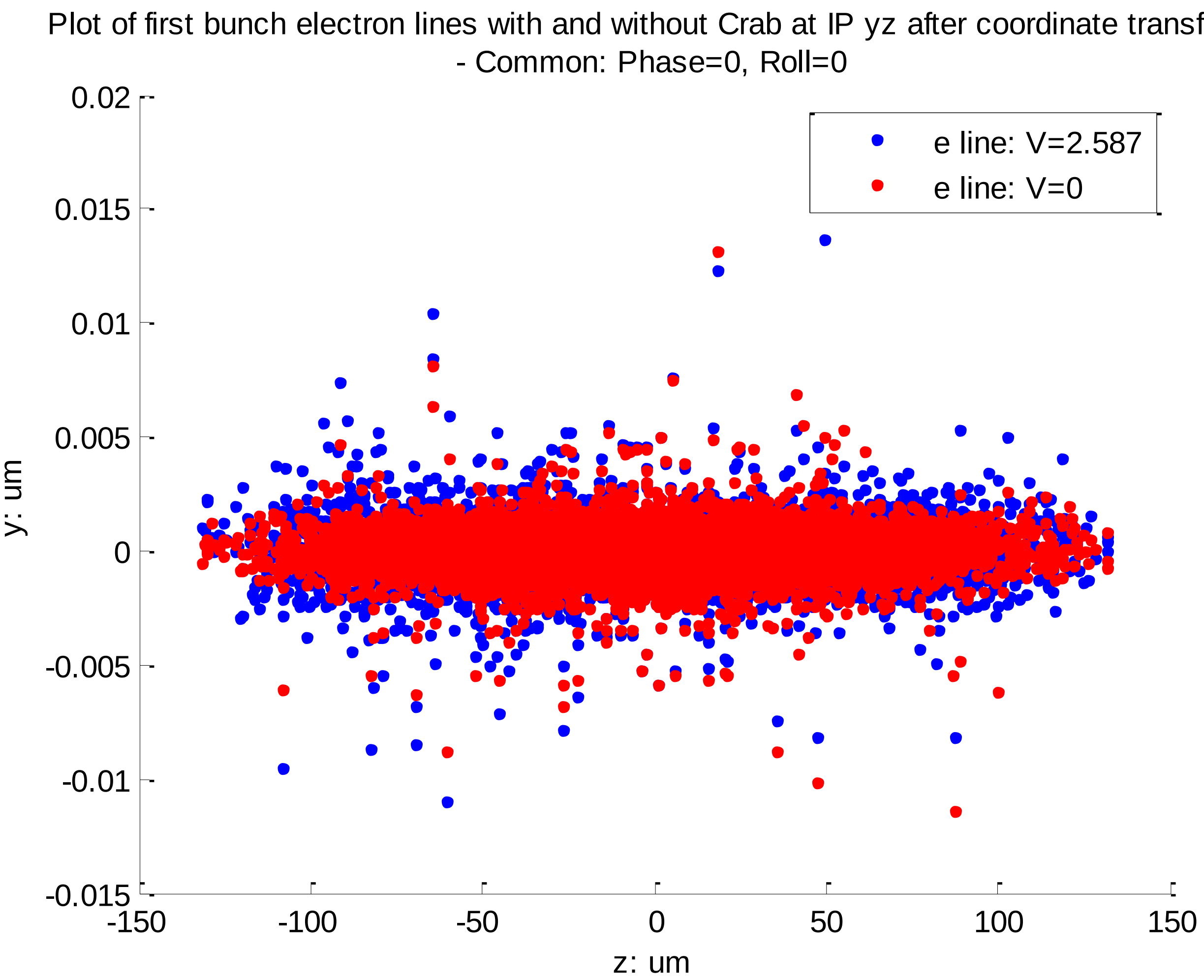
- Bunches are tracked from start of the BDS in PLACET to just in front of the IP (Crab Cavities in PLACET do not have exact implementation)
- Guinea-Pig then determines Luminosity with beam-beam effects
- Guinea-Pig needs a co-ordinate transform in PLACET to account for a crossing angle





Of course we cannot afford to lose 2% on amplitude errors if we have already lost 2% on phase errors

Vertical Expansion due to Crab Cavity

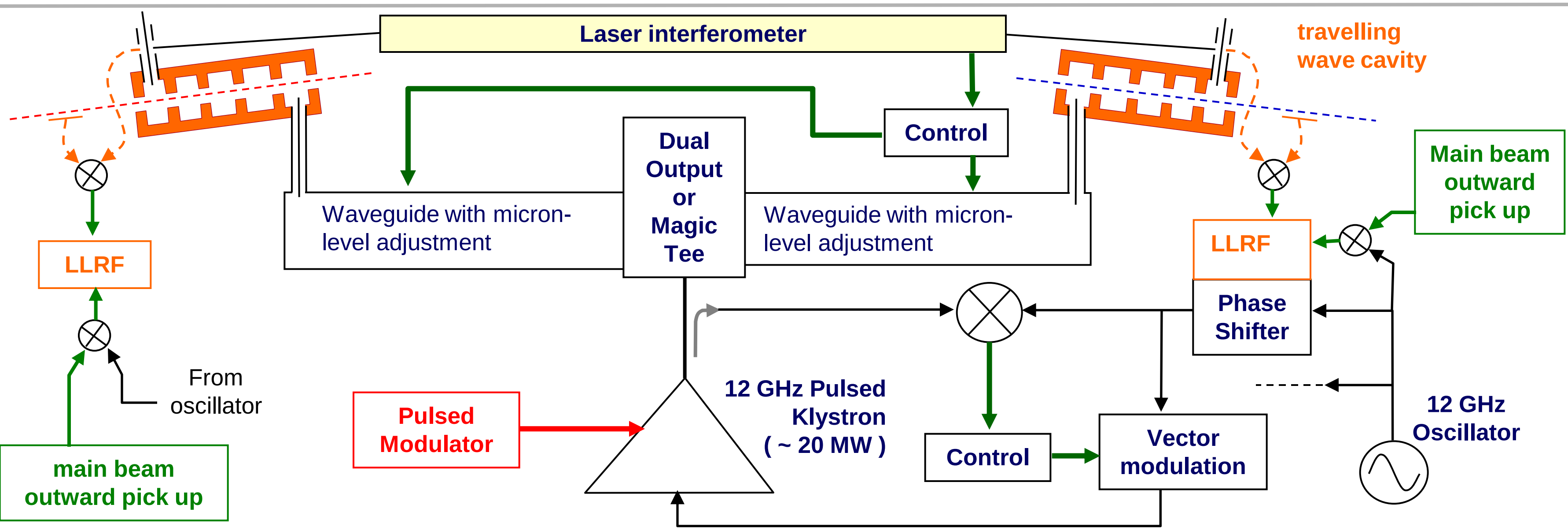


PLACET has been used to compare luminosity for head on collisions with luminosity for a crossing angle with perfect crabbing.

It appears that nonlinear components in the final focus give a small vertical blow up for a crabbed bunch.

The consequential luminosity loss has been estimated as between 5% and 10%

RF Layout and Procedure



Once the main beam arrives at the crab cavity there is insufficient time to correct beam to cavity errors. These errors are recorded and used as a correction for the next pulse.

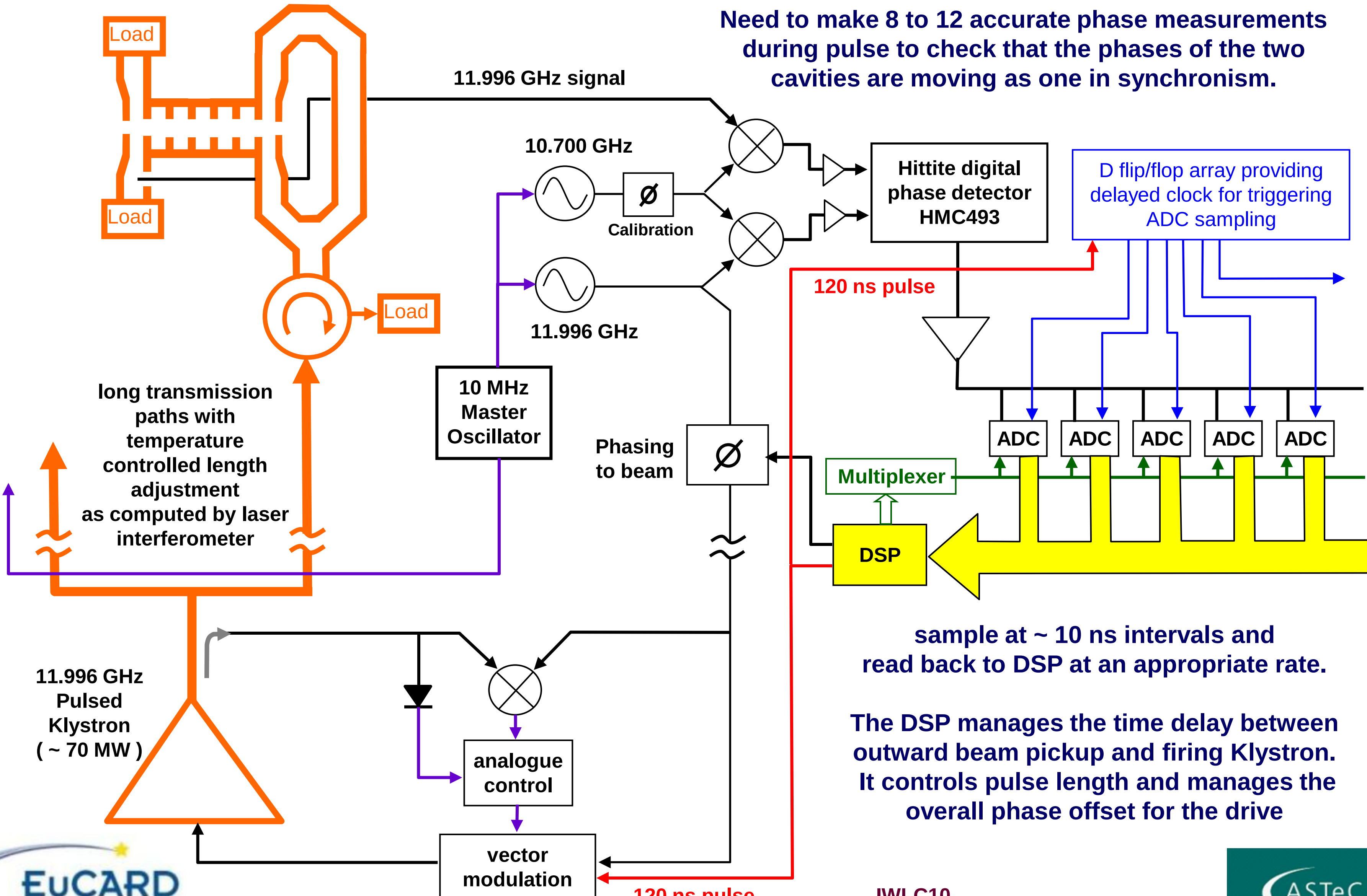
0. Send pre-pulse to cavities and use interferometer to measure difference in RF path length (option1)
1. Perform waveguide length adjustment at micron scale (option 2 use measurements from last pulse)
2. Measure phase difference between oscillator and outward going main beam
3. Adjust phase shifter 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

The Cockcroft Institute of Accelerator Science and Technology

Phase measurement for the 156ns pulse

LANCASTER UNIVERSITY

Need to make 8 to 12 accurate phase measurements during pulse to check that the phases of the two cavities are moving as one in synchronism.



sample at ~ 10 ns intervals and read back to DSP at an appropriate rate.

The DSP manages the time delay between outward beam pickup and firing Klystron. It controls pulse length and manages the overall phase offset for the drive

EuCARD

ASTeC

Damping Requirements

If the bunch repetition rate is an exact multiple of the unwanted modal frequency the induced wakefield has a phase such that it does not kick the beam. Maximum unwanted kick occurs for a specific frequency offset. This value must be used to determine damping.

For each unwanted mode determine the required external Q factor e.g.

G. Burt, R.M. Jones, A. Dexter, "Analysis of Damping Requirements for Dipole Wake-Fields in RF Crab Cavities." IEEE Transactions on Nuclear Science, Vol 54, No 5, pp 1728-1734, October 2007

For long bunch trains or low Qs one can use

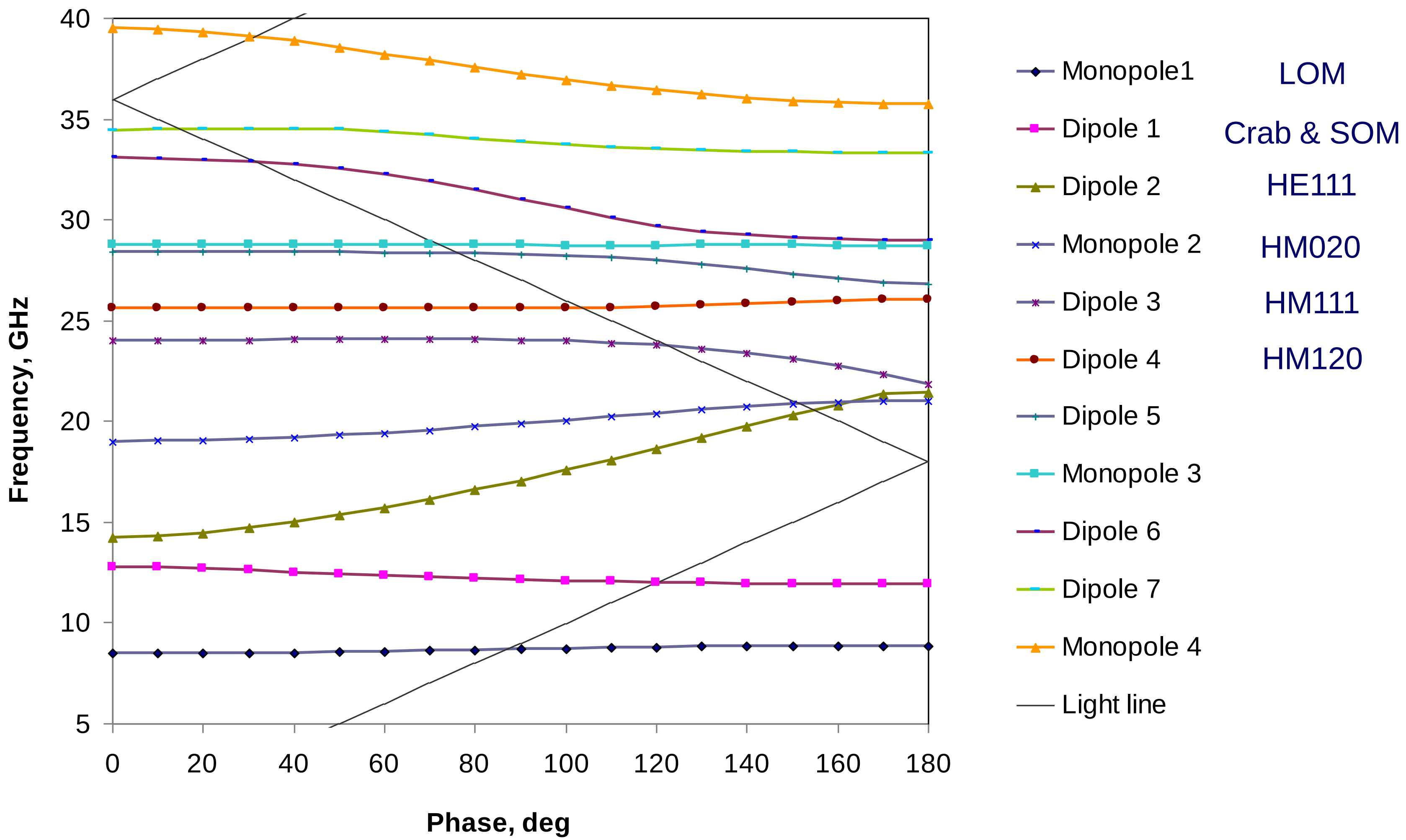
$$\frac{1}{Q_{ext,y}(m)} \approx \frac{2}{\omega_m t_b} \operatorname{cosech}^{-1}\left\{ \frac{4\,\Delta y_{ip}\,E}{q\,c\,r_{off}\;R_{34}\left(\frac{R}{Q}\right)_m} \right\}$$

(Use R_{12} for horizontal kicks)

m = mode
ω_m = mode freq.
t_b = bunch spacing
q = bunch charge
r_{off} = max bunch offset
E = bunch energy
Δy_{ip} = max ip offset
c = vel. light

This works for the SOM but the formulae for higher Qs is much longer

Dispersion Diagram for Modes



Wakefield study requires the eigenmode analysis of the 12 GHz cavity with periodic boundary condition

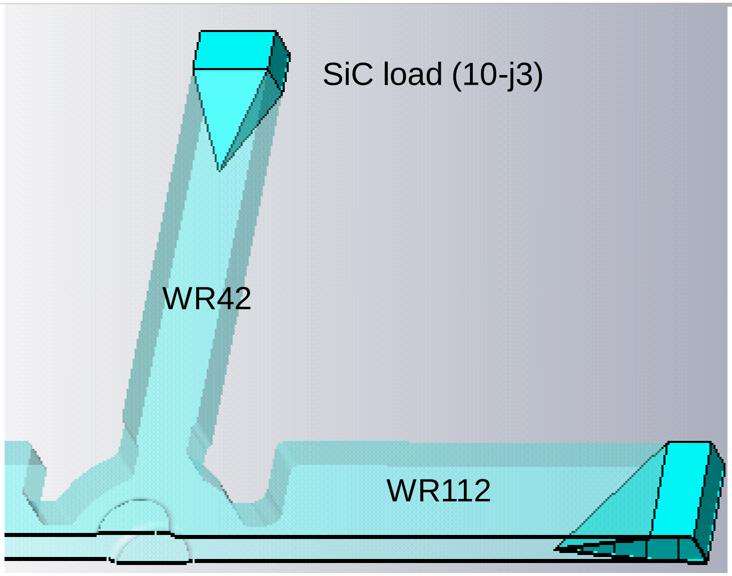
Damping Requirements

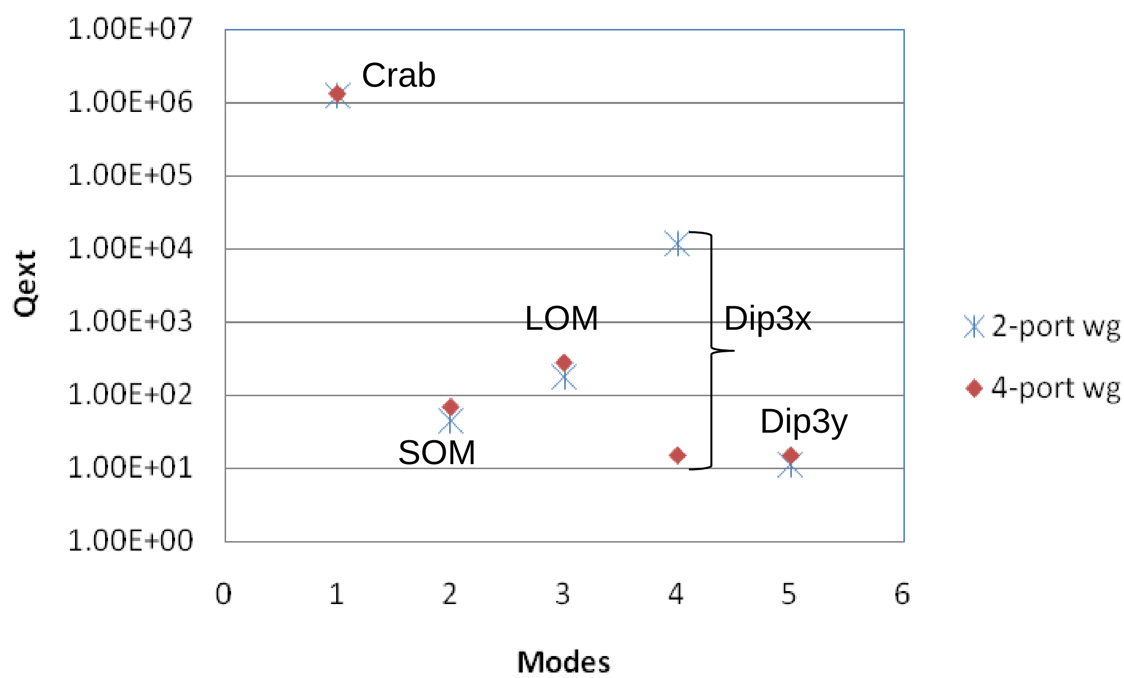
For 16 cell crab cavity , 3 TeV beam parameters and S > 0.98 dE/E, <1e-4%

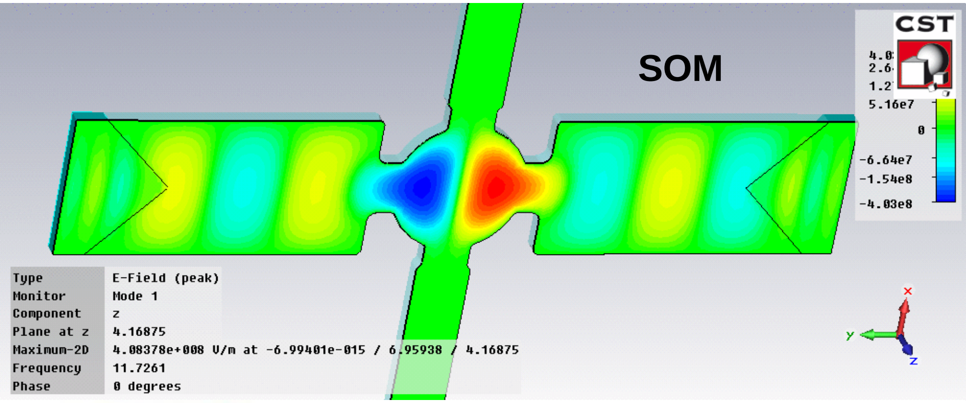
mode	Phase advance per cell	Sync. freq.	R/Q transv.	Req. Q_x	Req. Q_y
	degrees	GHz	Ω		
Dipole 1 (Crab,SOM)	120.0	11.994	53.9		40
Dipole 2 (HE111)	155.0	20.360	0.174	7610	7130
Dipole 3 (HM111)	122.5	24.066	4.002	281	263
Dipole 4 (HM120)	102.5	25.634	1.84	571	535
Dipole 5	75.5	28.349	0.041	23464	21982
Dipole 6	30.0	32.885	1.075	763	715
mode	**Phase advance per cell**	**Sync. freq.**	**R/Q longd.**	**Req. Q_o**	
Monopole 1 (LOM)	87.5	8.668	94.758	832	-
Monopole 2 (HM020)	152.5	20.845	51.280	1536	-

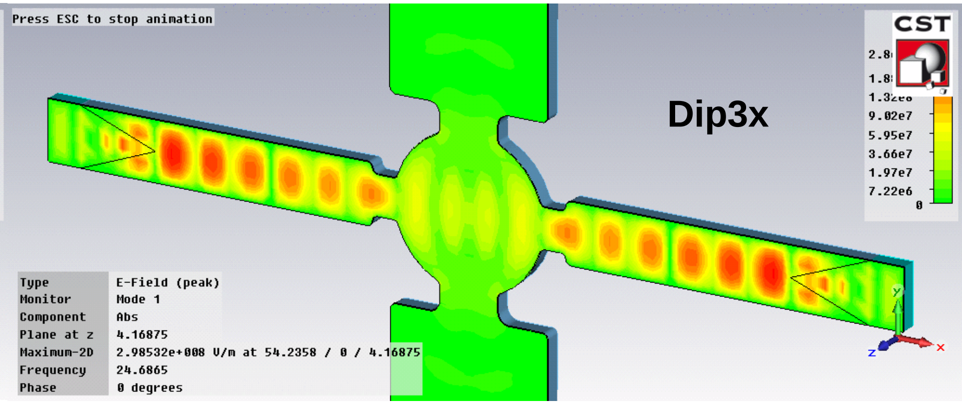
sig_x = 153μm, sig_y = 35.3μm

Mode damping



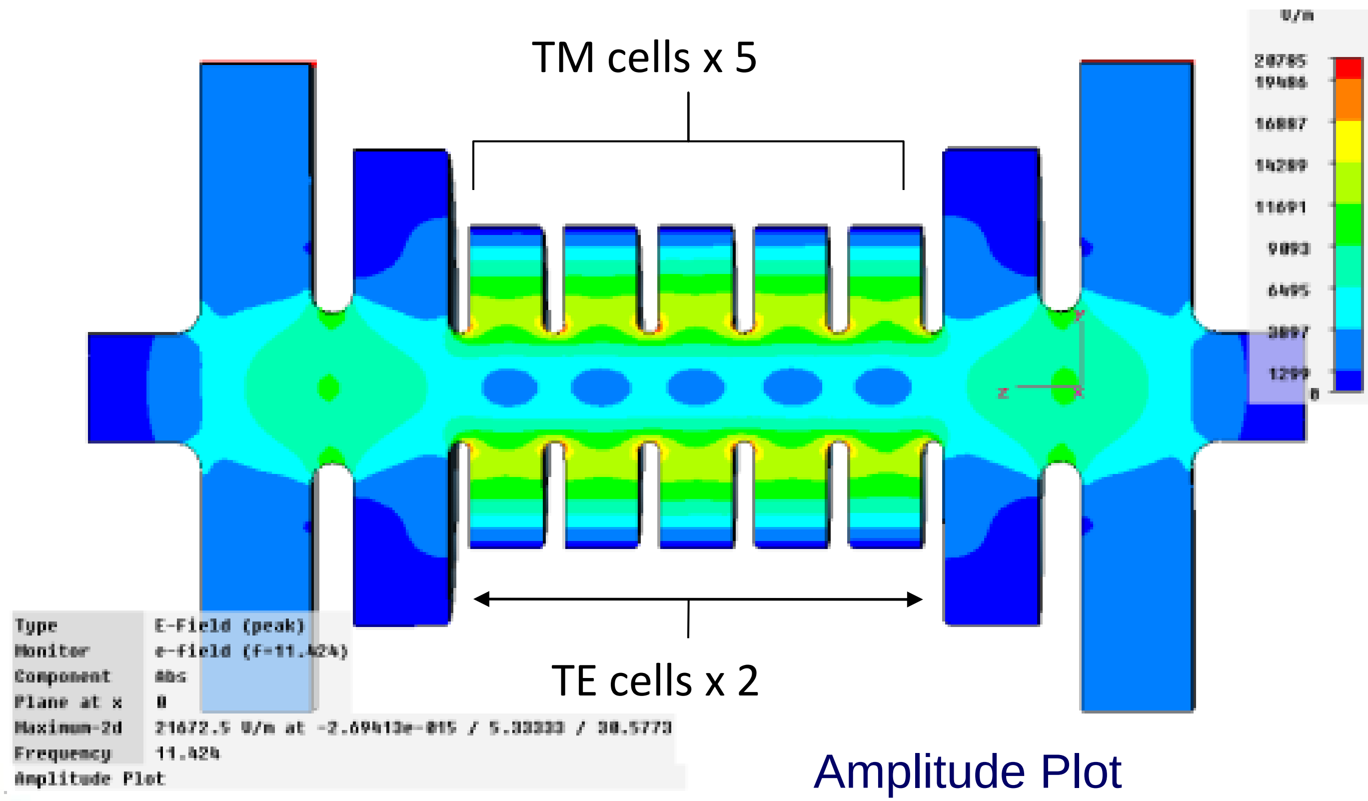






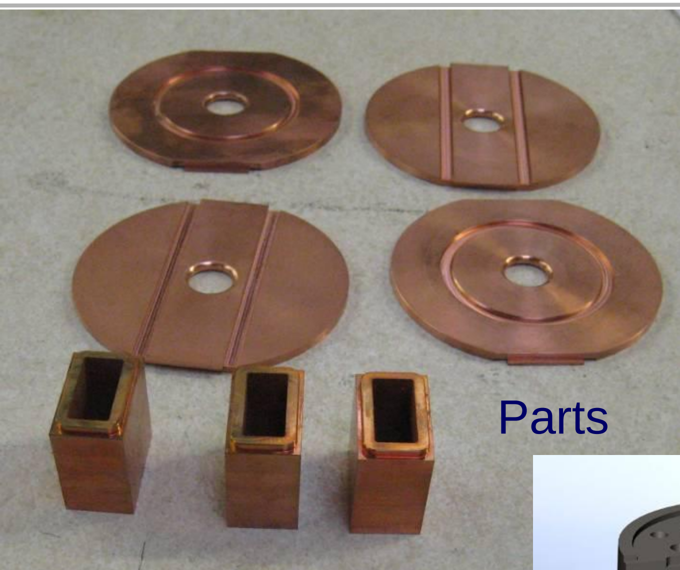
Gradient Testing

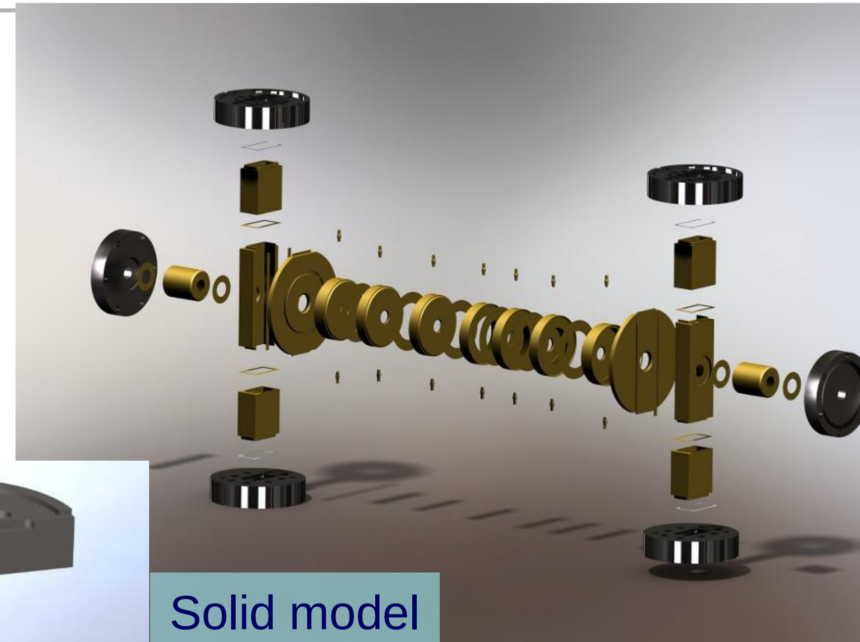
- To determine the maximum operating gradient for the CLIC crab cavity a special design of test cavity, compatible with the SLAC high power klystron and test stand is needed. It has been designed and is being manufactured.
- The mid cells operate at TM_{110} dipole mode for maximum axial field while the matching end cells at TE_{111} dipole mode so that axial field =0



Amplitude Plot

Cavity Under Construction


Parts


Solid model