CLIC Crab Cavities

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(on behalf of the LC Crab System Collaborations)

CERN

14th October 2009

Contributors

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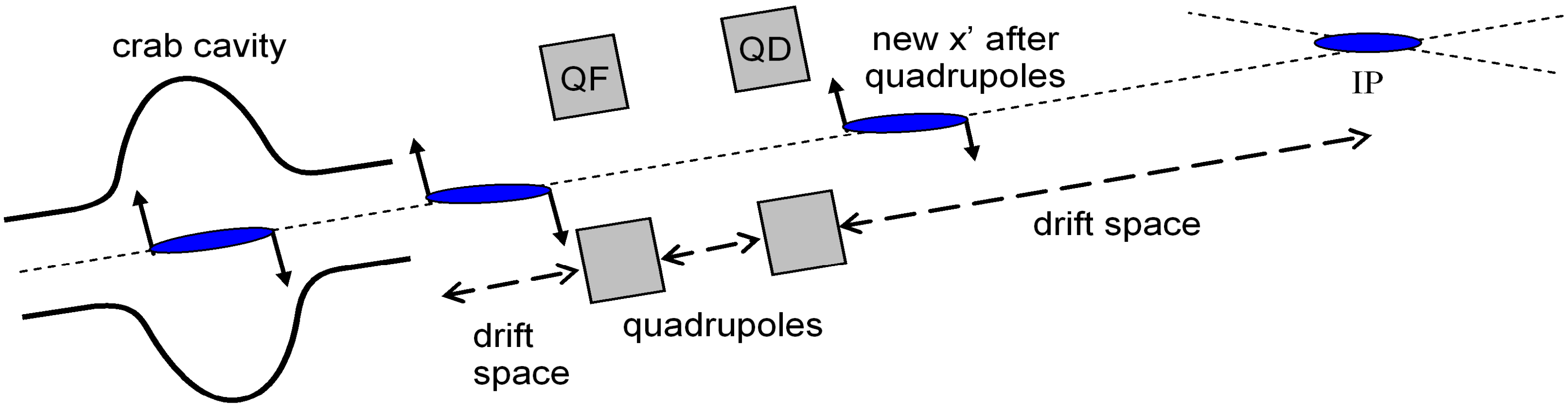
Crab Cavity Function



The crab cavity is a deflection cavity operated with a 90° 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

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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

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Planned Approach

- Design 12 GHz TW dipole copper cavity with high group velocity and thick irises
  - 12 GHz is compact and has synergy with linac
  - 12 GHz makes phase control tolerance larger than for sub harmonic frequency choices
  - TW allows energy flow to mitigate beam-loading
  - Thick irises reduces effects of pulse heating and phase drift
  - Adjacent mode for SW cavities affect phase control performance
- Investigate various damping options
- Compute wakefields for designs with varied damping options
- If none of the damping schemes meet the specification then scale to lower frequency for smaller kicks
- Use single Klystron to drive both cavities
  - Phase stability of Klystrons and the PET structures is very poor with respect to the cavity to cavity specification

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

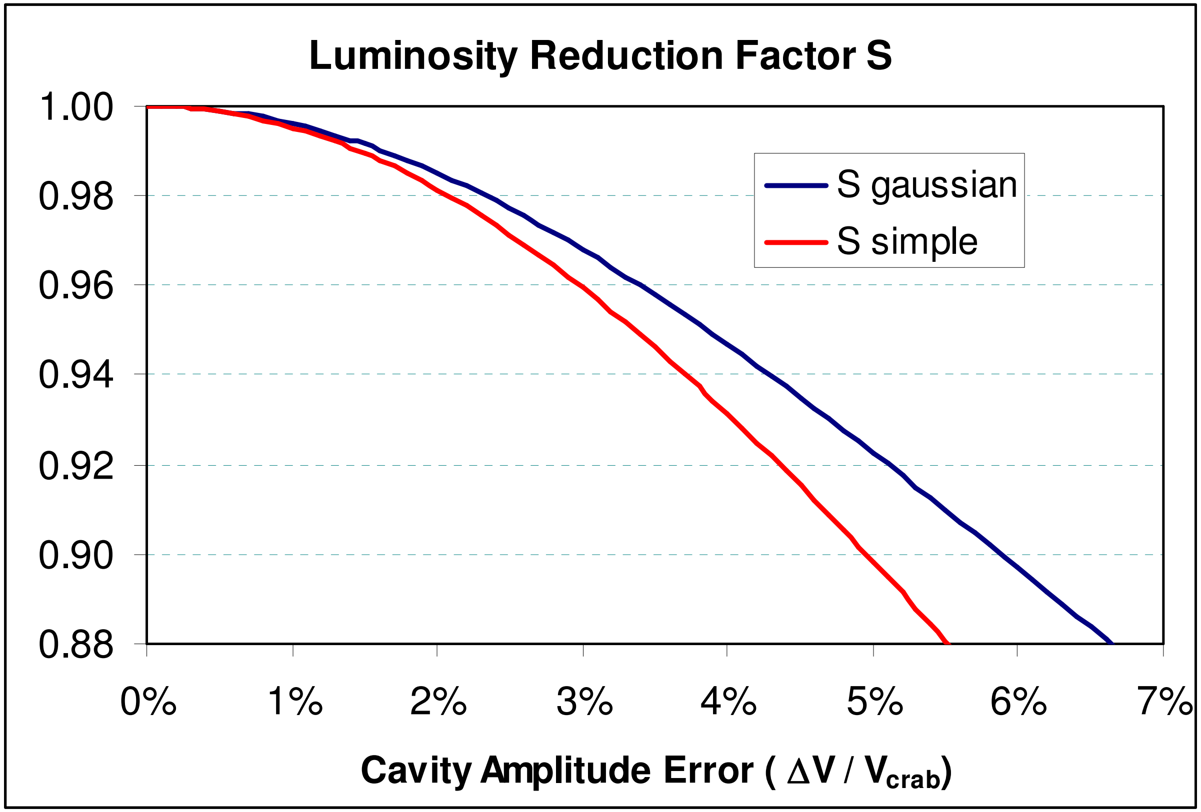
$$V_{crab} = \frac{\theta_r E_o c}{R_{12}\omega} = \frac{10^{-2} \times 1.5 \times 10^{12} \times 3 \times 10^{8}}{25 \times 2\pi \times 12 \times 10^{12}} = 2.4\,\mathrm{MV}$$

Error in kick gives tilts effective collision from head on.

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

Tolerance for Gaussian Amplitude Errors



$\sigma_z = 44000$ nm

$\sigma_x = 45$ nm

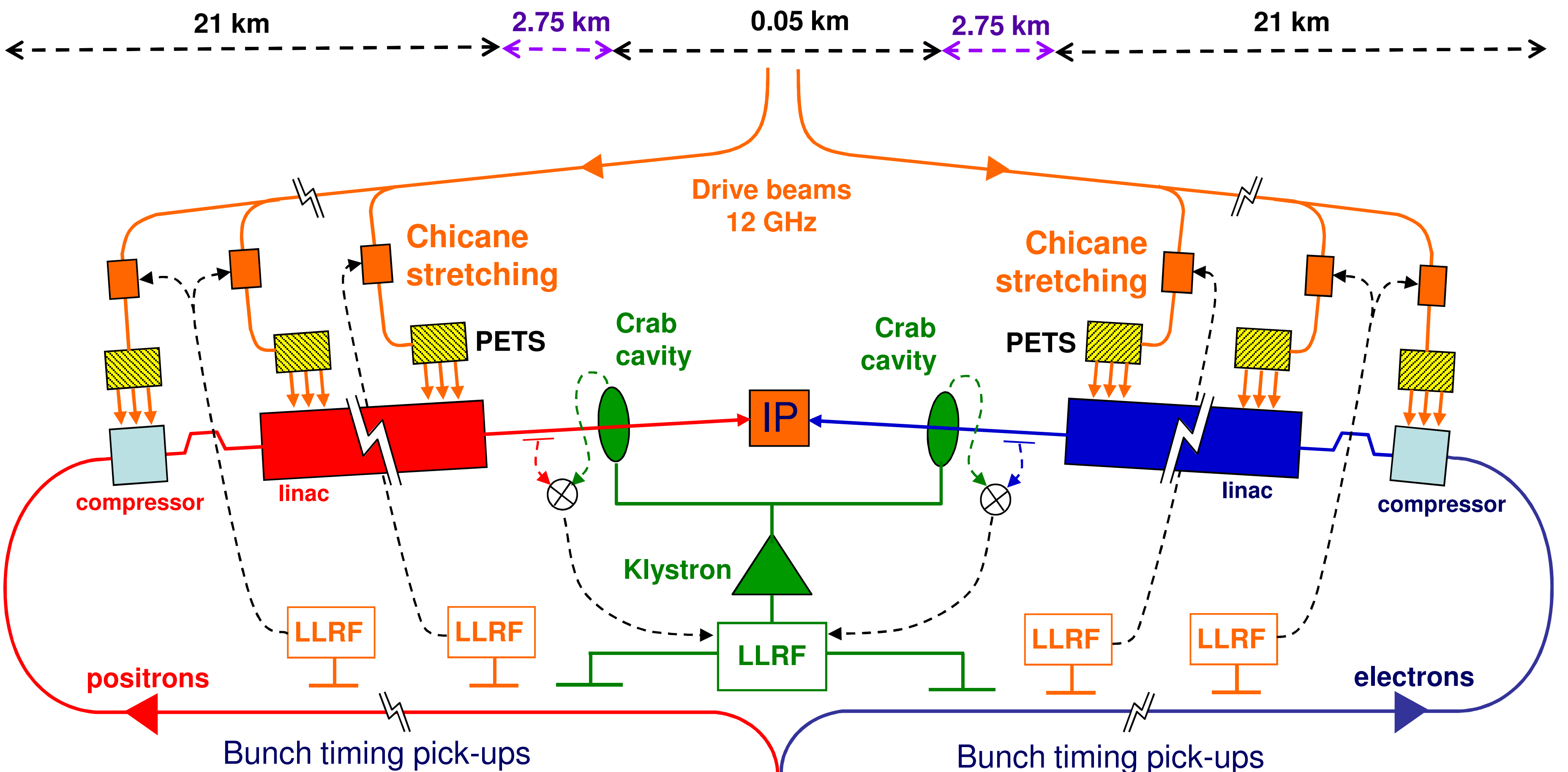
$\theta_c = 0.02$ rad

$$\bar{S}\left(\frac{\Delta V}{V_{crab}}\right) = \frac{1}{2\pi\left(\frac{\Delta V}{V_{crab}}\right)^2}\int_{-\infty}^{\infty}\frac{dV_1}{V_{crab}}\int_{-\infty}^{\infty}\frac{dV_2}{V_{crab}}\frac{\exp\left\{-\frac{(V_1/V_{crab})^2}{2(\Delta V/V_{crab})^2}\right\}\exp\left\{-\frac{(V_2/V_{crab})^2}{2(\Delta V/V_{crab})^2}\right\}}{\sqrt{1+\left\{\frac{\sigma_z\theta_c}{4\sigma_x}\frac{(|V_1|+|V_2|)}{V_{crab}}\right\}^2}}$$

CLIC work program (EUCARD and CI)

1. Investigate maximum gradient vs. pulse length for X-band dipole structure at SLAC
2. Investigate pulse heating for dipole structures and its effect on phase stability.
3. Develop adequately damped structures.
4. Cooling requirements and mechanical design.
5. Determine likely phase and amplitude control performance for operation from a Klystron.
6. Develop RF drive, distribution and control concepts.
7. Design beam test experiments.

CLIC LLRF Timing



2 GHz bunch rep

Crab bunch timing pickups could be 2.75 km away from LLRF

Booster Linac
561 m
2.2 to 9.0 GeV

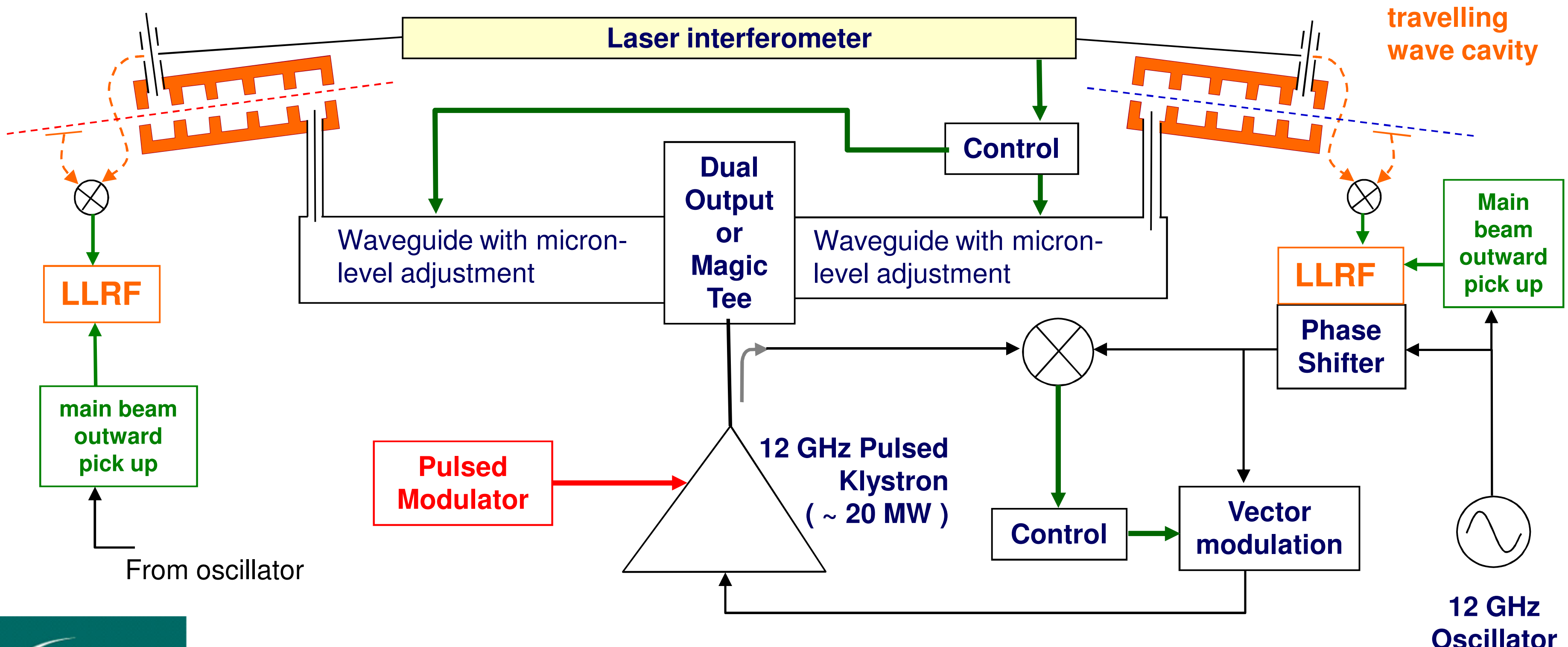
Synchronisation to main beam after booster linac. For a 21 km linac we have 140 μs between bunches leaving the booster and arriving at the crab cavities.

Crab Cavity RF

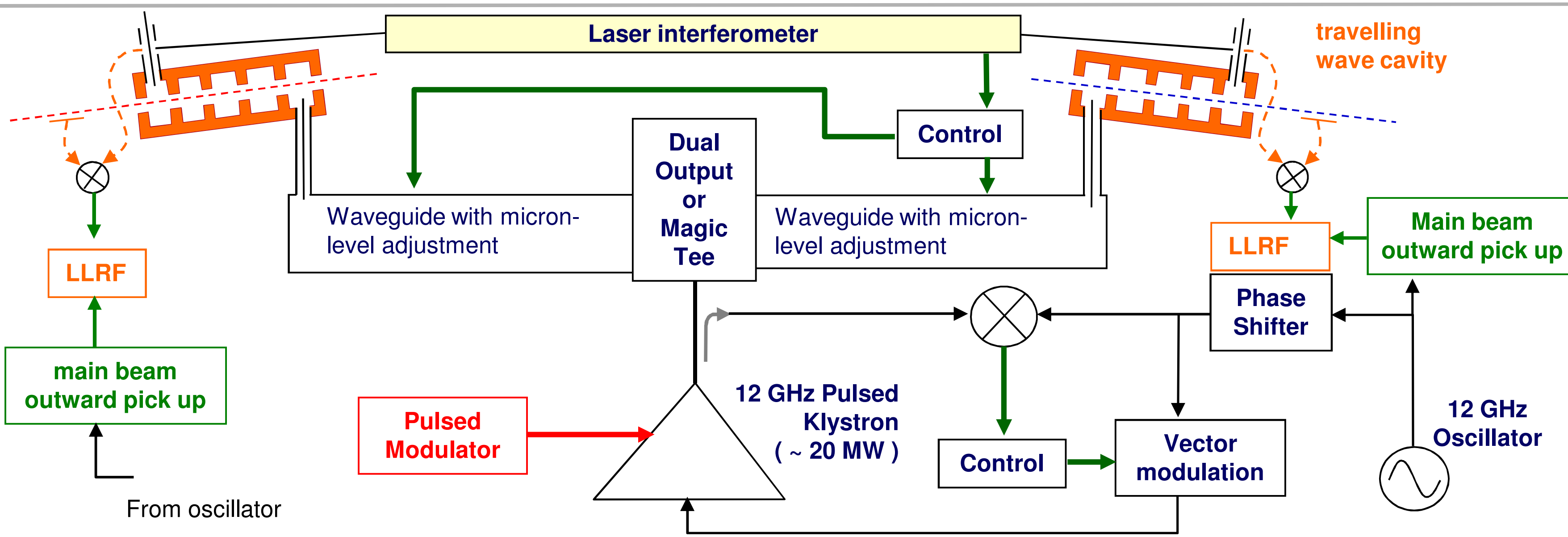
- Beamloading constrains us to high power pulsed operation
- Intra bunch phase control looks impossible for a 140 ns bunch

SOLUTION

- One Klystron (~ 20 MW pulsed) with output phase and amplitude control
- Intra bunch delay line adjustment for phase control (i.e. between bunch trains)
- Very stable cavities



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.

1. Send pre-pulse to cavities and use interferometer to measure difference in RF path length
2. Perform waveguide length adjustment at micron scale
3. Measure phase difference between oscillator and outward going main beam
4. Adjust phase shifter in anticipation of round trip time and add offset for main beam departure time
5. Klystron output is controlled for constant amplitude and phase
6. Record phase difference between returning main beam and cavity
7. Alter correction table for next pulse

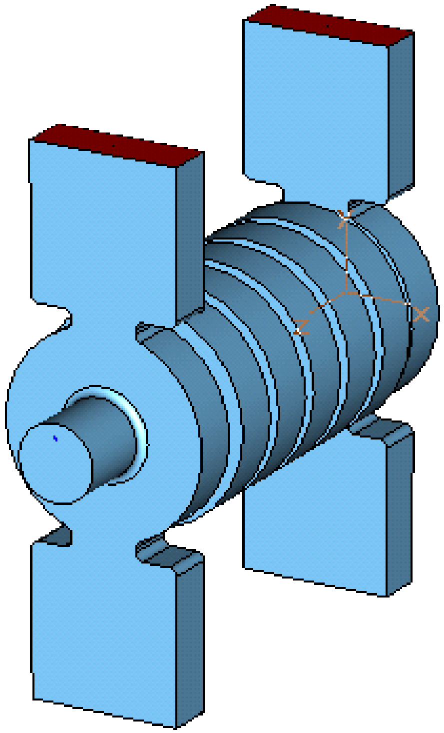
Travelling Wave Structure

Parameter search presented last year suggested

- $2\pi/3$ mode for maximum group velocity
- 5 mm iris radius for short range wakes without compromising group velocity
- less than 3 mm iris thickness for high R/Q and Q.

Parameters for current design work

cell length ($2\pi/3$ mode)	8.3375	mm
iris thickness	2.0	mm
iris radius	5.0	mm
equator radius (determines freq.)	14.0904	mm
Group velocity	2.95%	of c
R/Q	53.92	Ω
E surface / E transverse	2.726	
H surface / E transverse	0.0095	S



Change in group velocity from last year is due to mesh refinement

Beamloading in 16 Cell Cavity

Cavity Parameters as on last slide and Q = 6381

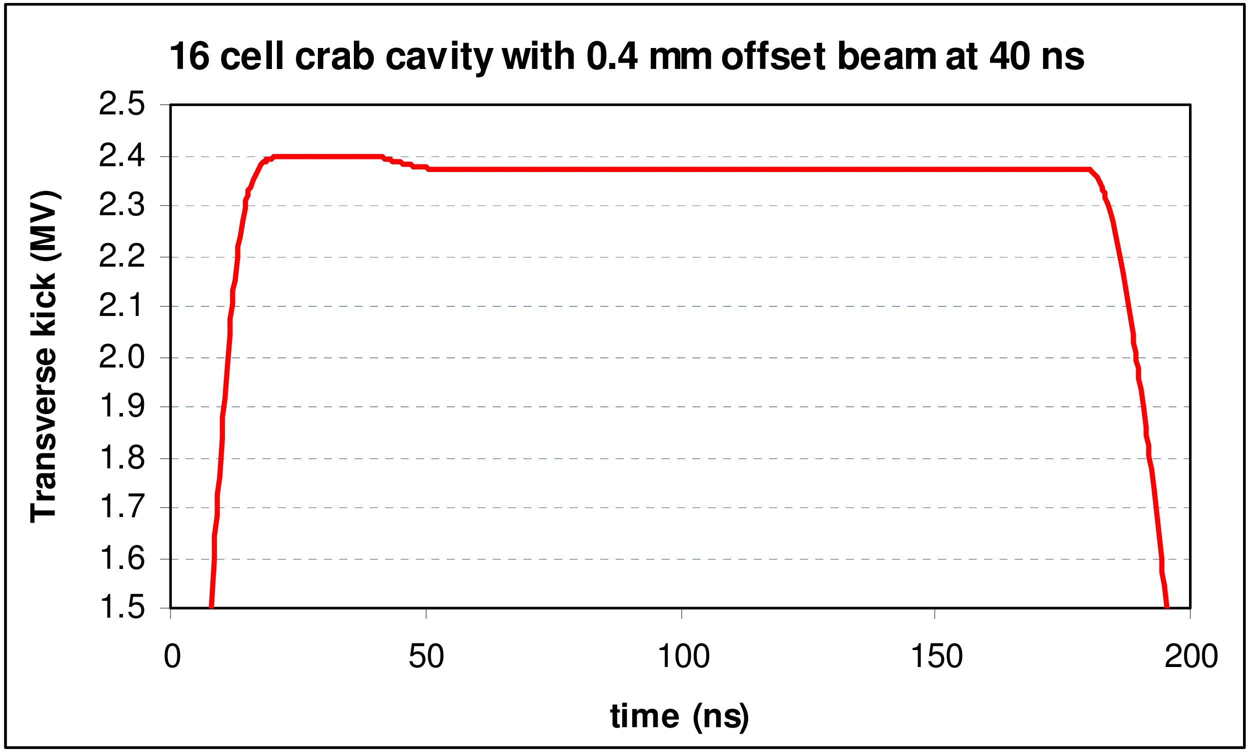
Beam offset (mm)	-0.4	0.0	0.4
Power entering cell 1 (MW)	6.388	6.388	6.388
Power leaving cell 16 (MW)	5.619	5.341	5.063
Ohmic power loss (MW)	1.071	1.047	1.023
Beamload power loss (MW)	-0.302	0.000	0.302
E max for cell 1 (MV/m)	51.1	51.1	51.1
Efficiency	12.04%	16.39%	20.74%
Kick (MV)	2.428	2.400	2.372

A short inefficient cavity with a high power flow achieves adequate amplitude stability

Can we make the gradient?

Is pulse heating OK (consider low temperature operation)?

Fill Time and Beamloading



Input = 6.45 MW
Initial kick = 2.40 MV
Plateau = 2.37 MV

v_g = group velocity
L_{cell} = cell length
U_n = energy in cell n
f_{rep} = bunch frequency
q = bunch charge
δx = bunch offset

For each cell solve energy equation

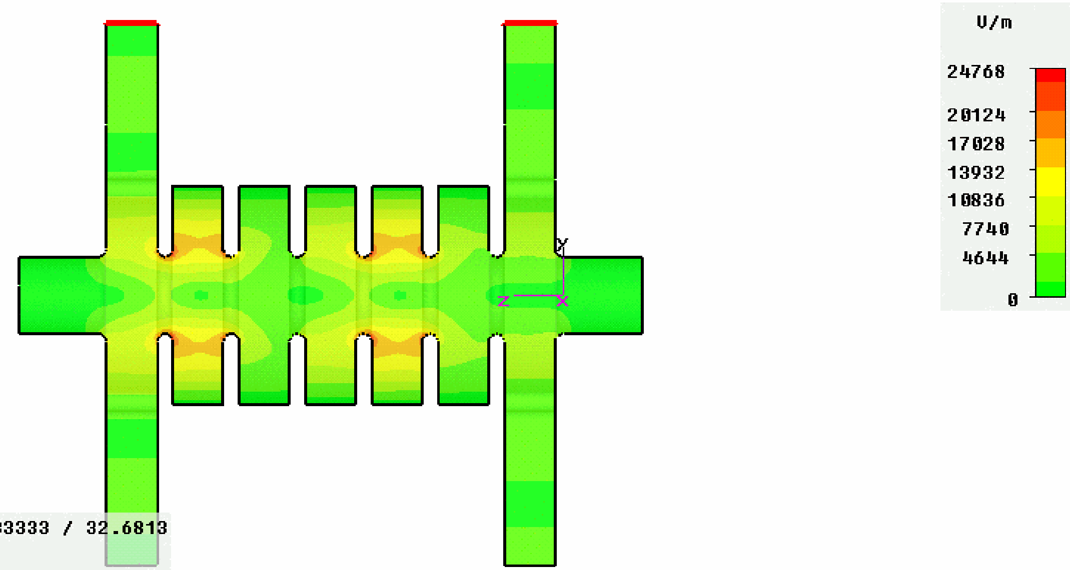
$$\frac{dU_n}{dt} = \frac{(U_{n-1} - U_n)}{L_{cell}} v_g \quad - \quad U_n \frac{\omega}{Q} \quad - \quad q\, f_{rep}\, \delta x\, \omega \sqrt{\frac{\omega}{c} \frac{R}{Q} U_n} \qquad (n > 1)$$

convection - dissipation - beamloading

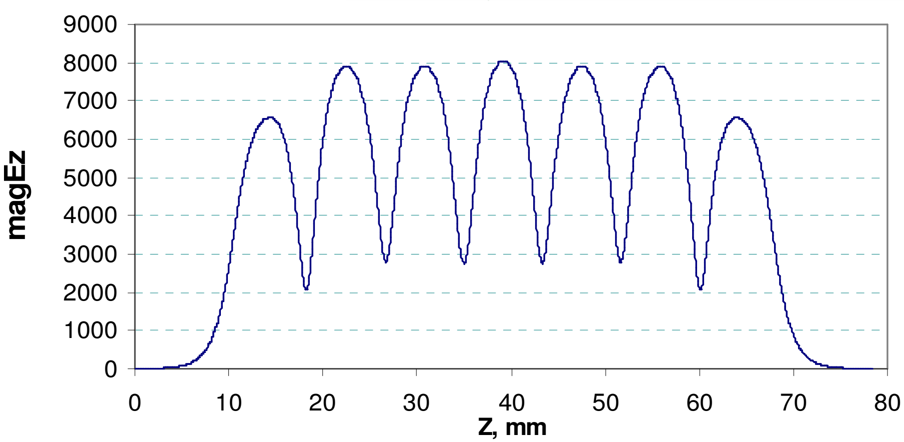
Simulation with MWS

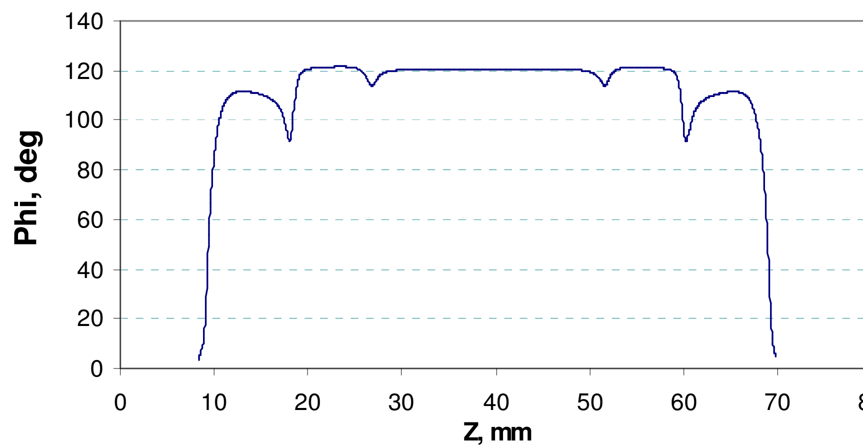
Design variables

Equator radius and coupling slot dimensions of the end cell



Type	E-Field (peak)
Monitor	e-field (f=11.9942)
Component	Abs
Plane at x	0
Maximum-2d	25826.6 V/m at 0 / 5.33333 / 32.6813
Frequency	11.9942
Phase	0 degrees





Field flatness and phase advance

Damping Requirements

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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 one can use

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

- 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

(Use R_{12} for horizontal kicks)

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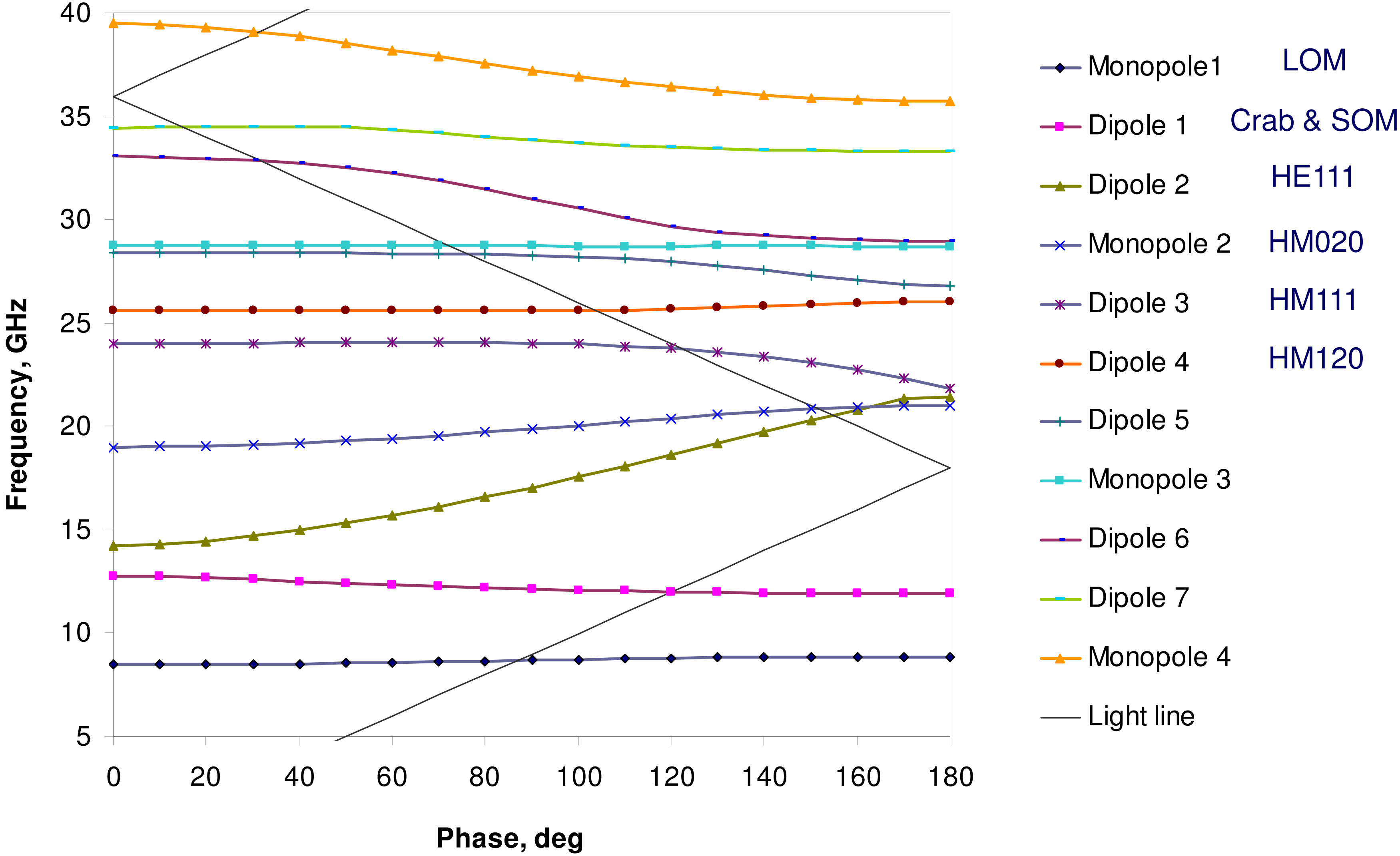
Dispersion Diagram for Modes



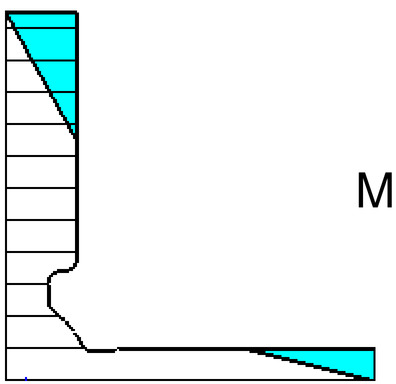
Damping Requirements

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

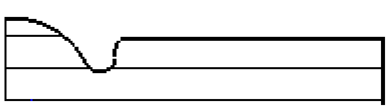
mode	Phase advance per cell	Sync. freq.	R/Q transv.	Req. Q_x	Req. Q_y
	degrees	GHz	Ω		
Dipole 1 (Crab,SOM)	120.0	11.994	53.9		15
Dipole 2 (HE111)	155.0	20.360	0.174	15500	2170
Dipole 3 (HM111)	122.5	24.066	4.002	569	83
Dipole 4 (HM120)	102.5	25.634	1.84	1160	165
Dipole 5	75.5	28.349	0.041	47670	6700
Dipole 6	30.0	32.885	1.075	1550	220
mode	**Phase advance per cell**	**Sync. freq.**	**R/Q longd.**	**Req. Q_o**	
Monopole 1 (LOM)	87.5	8.668	94.758	416	-
Monopole 2 (HM020)	152.5	20.845	51.280	768	-

Waveguide Damping

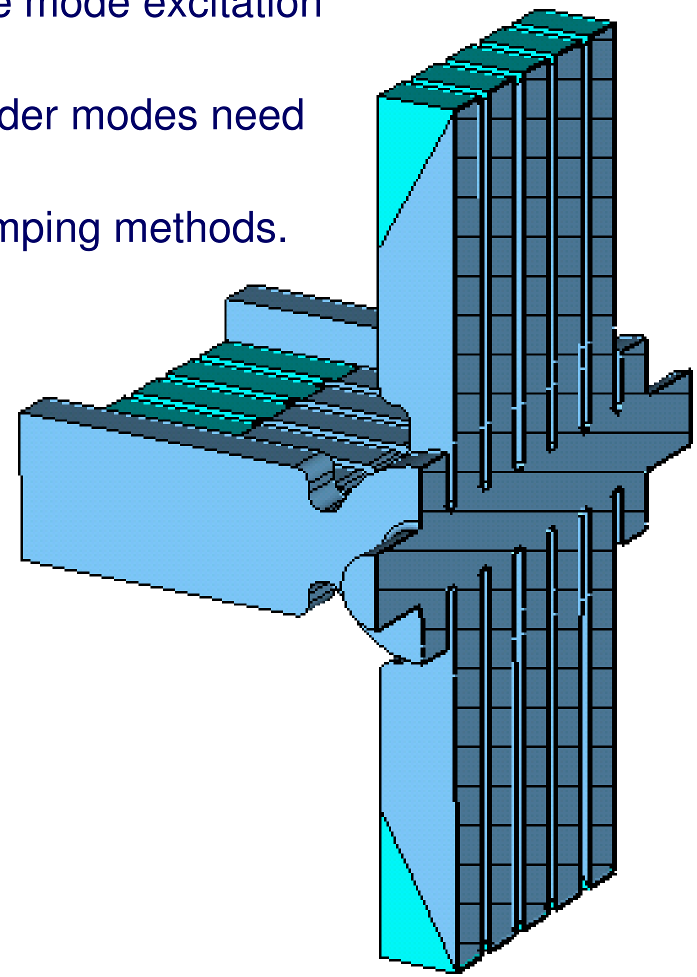
- Due to high R12 and R34 transport elements in the crab cavity location and small transverse beam sizes at the IP, bunch alignment jitter at the IP is very sensitive to higher order dipole mode excitation of the Crab Cavity.
- Basic calculations suggest the Same and Higher order modes need to be damped to Q factors in the range 10 - 100.
- This tolerance is difficult to meet with traditional damping methods.



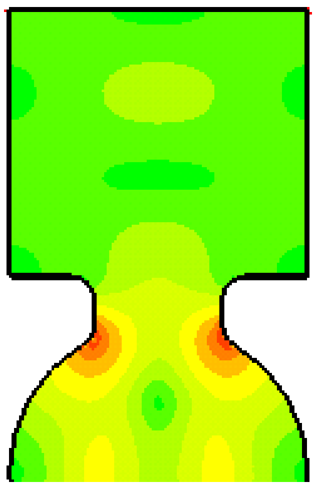
Mid cells

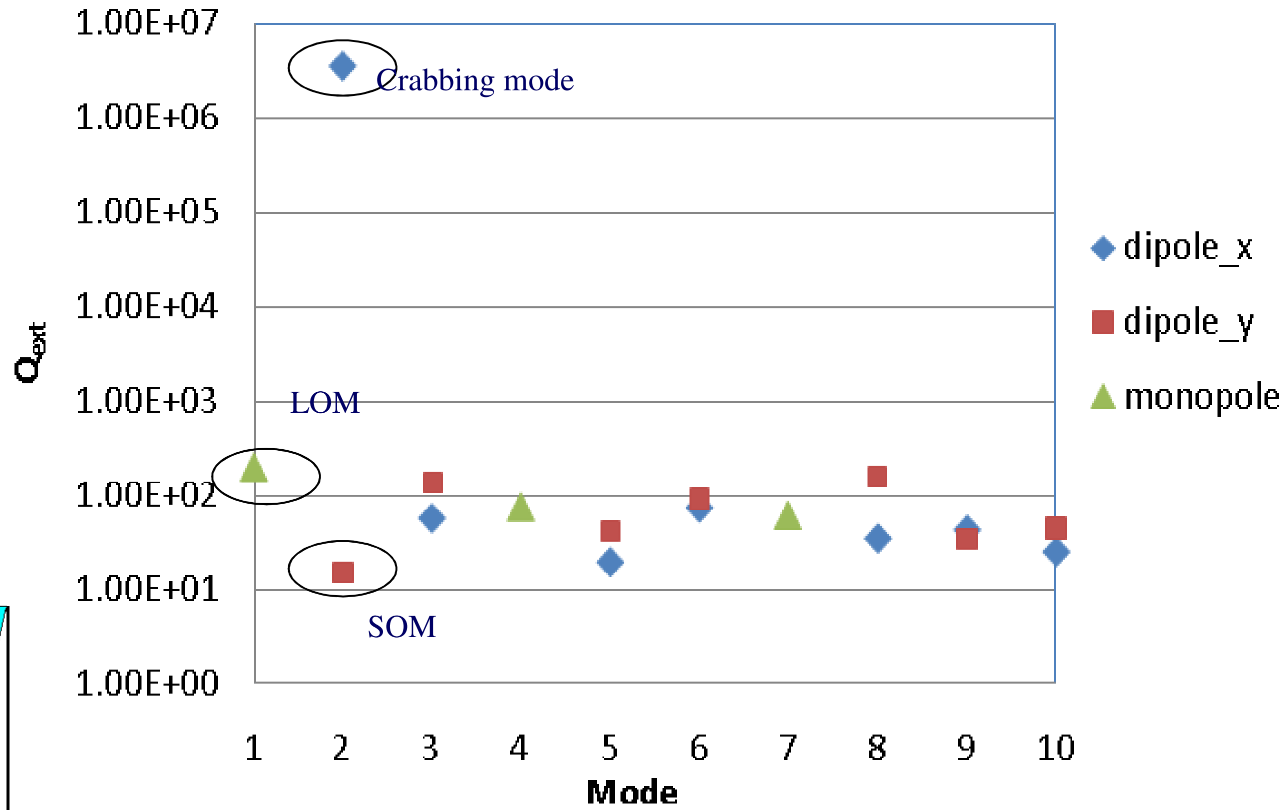


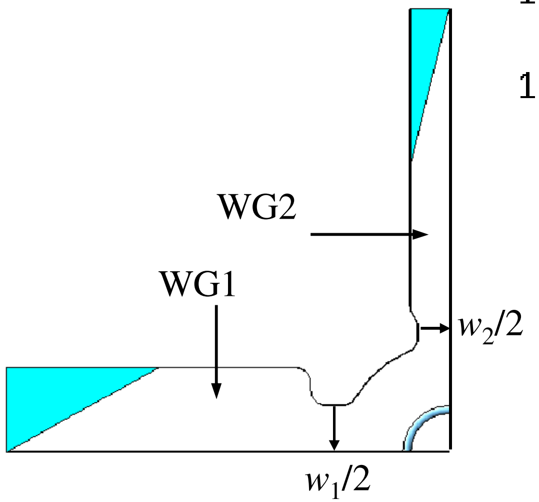
End cells



Mode Damping

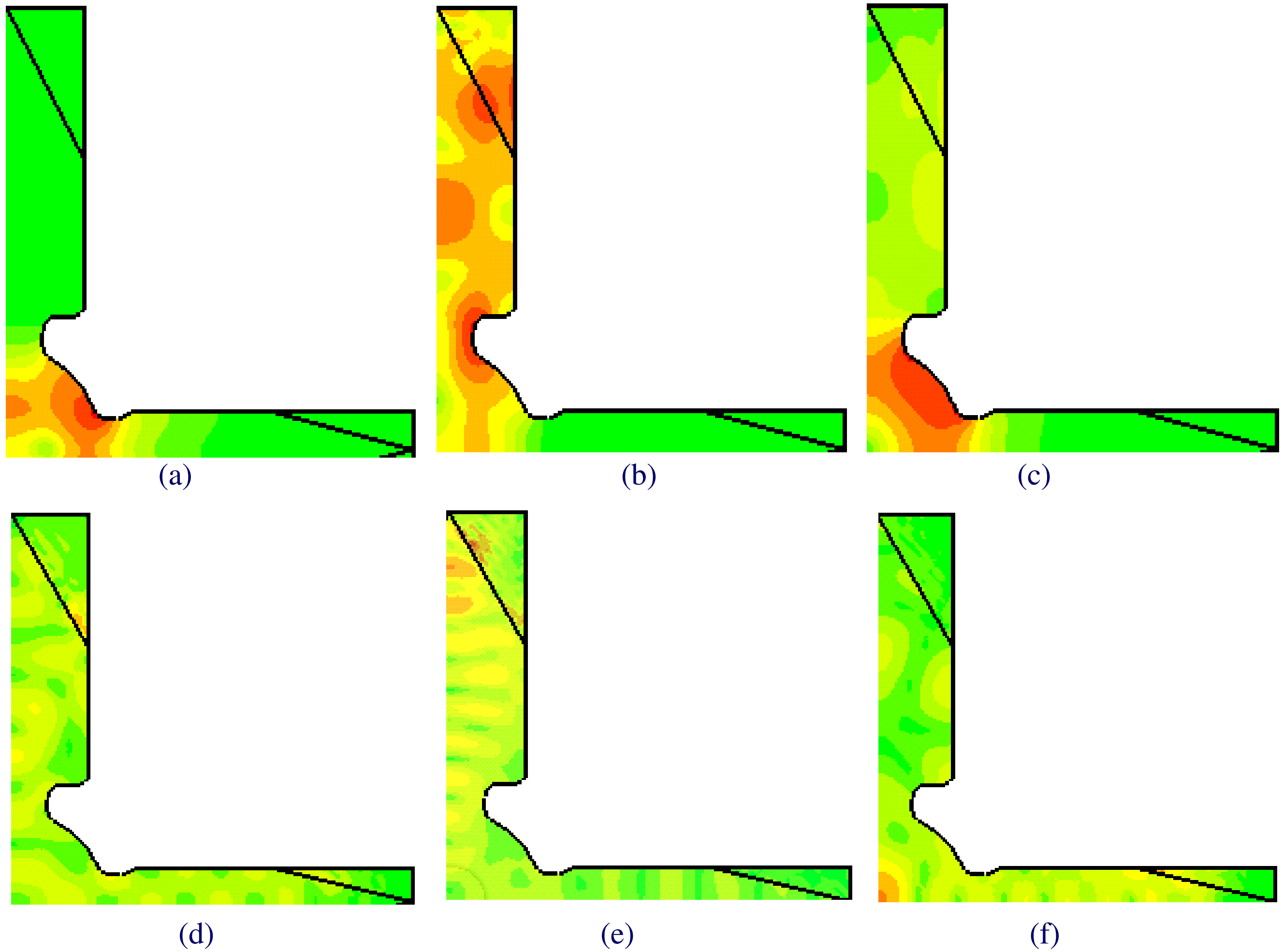






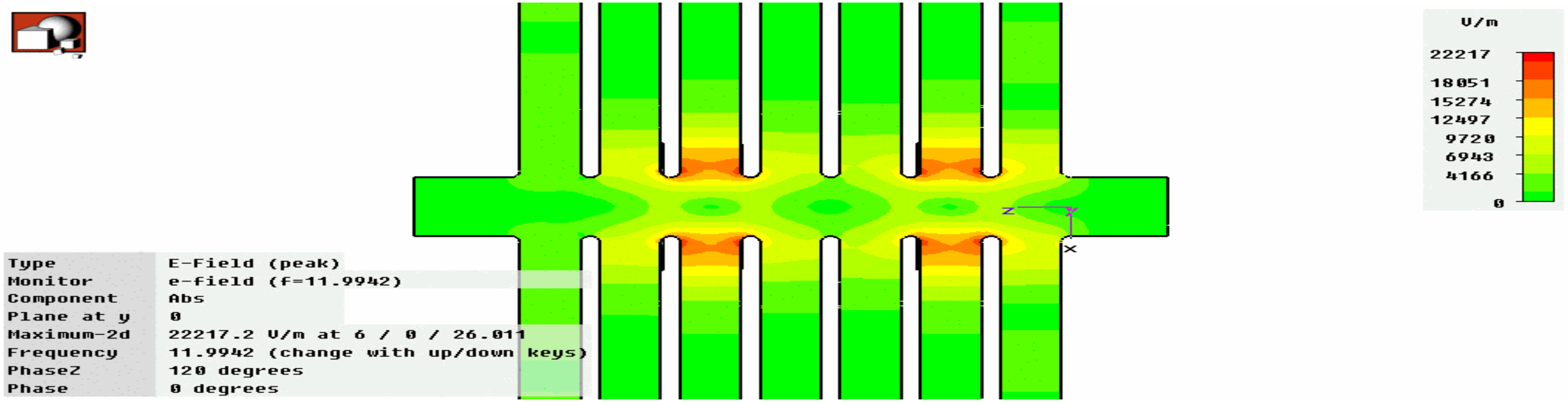
Note – calculation used single cells with perfectly conducting boundaries but realistic conductivity for SiC.

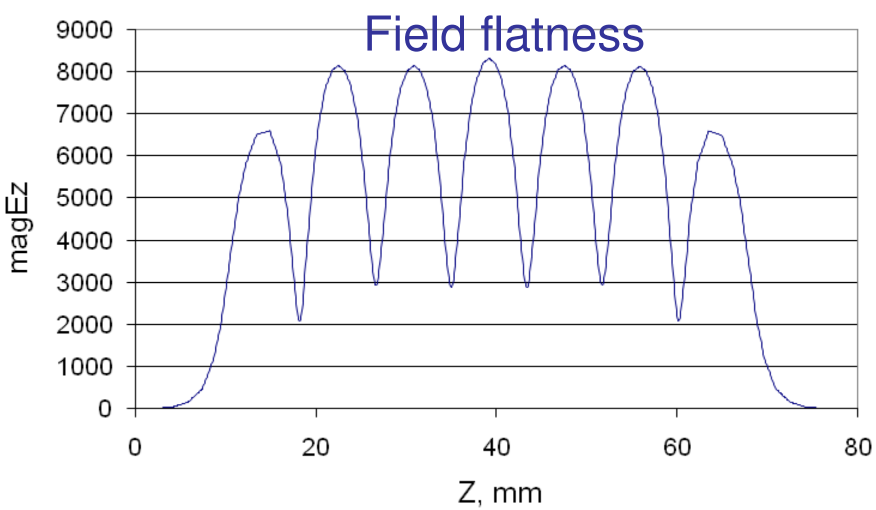
Plot of magnitude H field

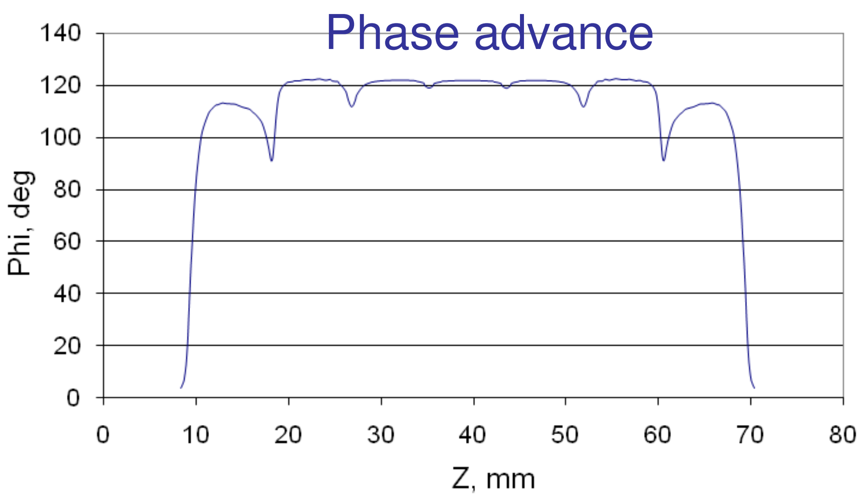


(a) Crab (b) SOM and (c) LOM (d) Mode 4 (e) Mode 8_x (f) Mode 8_y

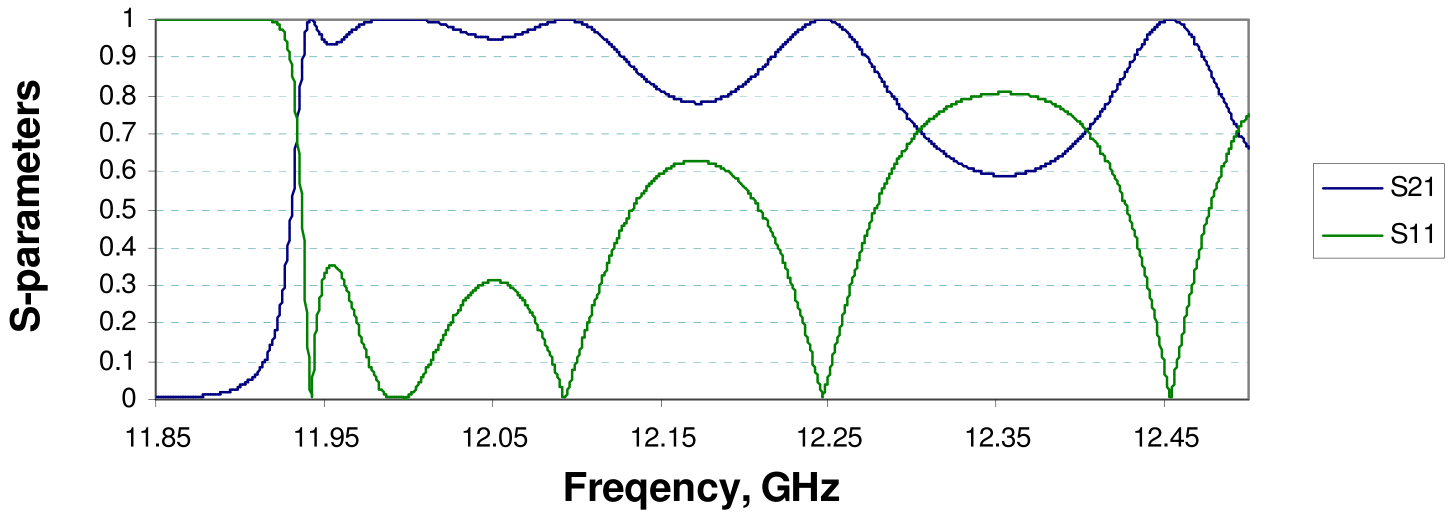
Simulation of Damped Structure



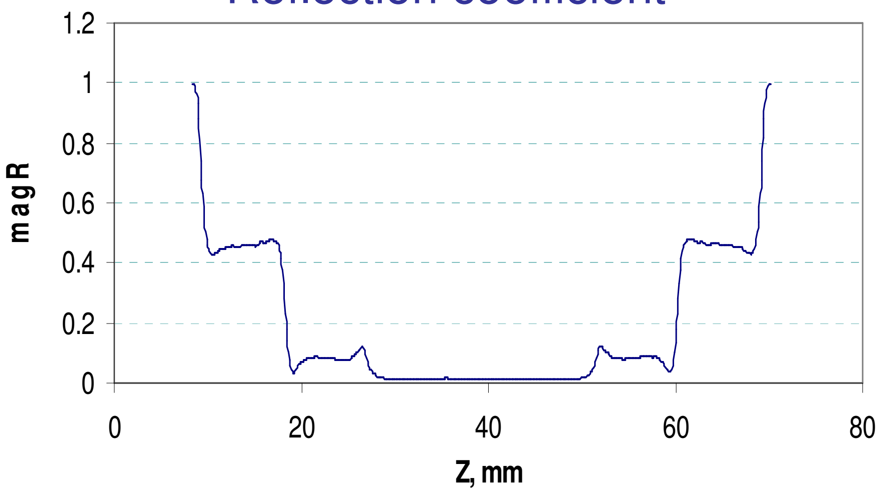




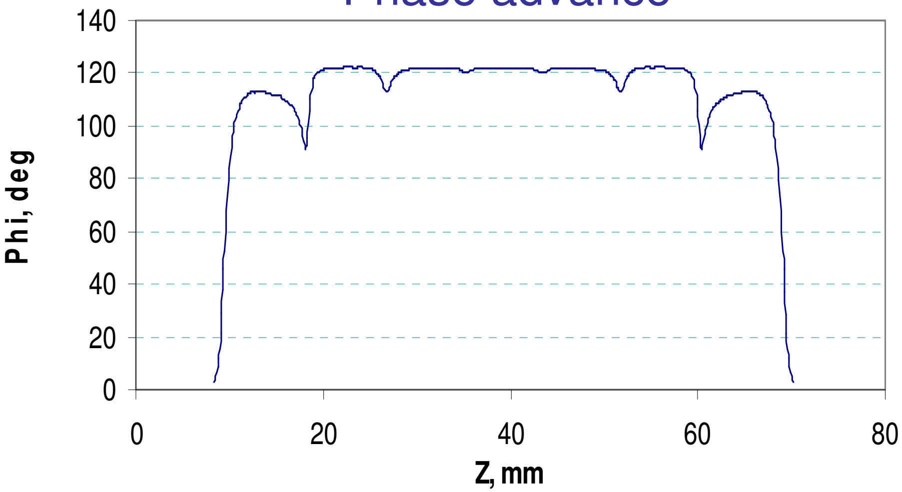
S-Parameters for Damped Structure



Reflection coefficient

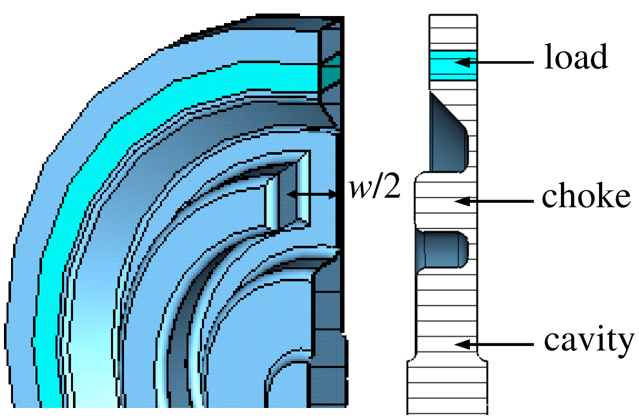


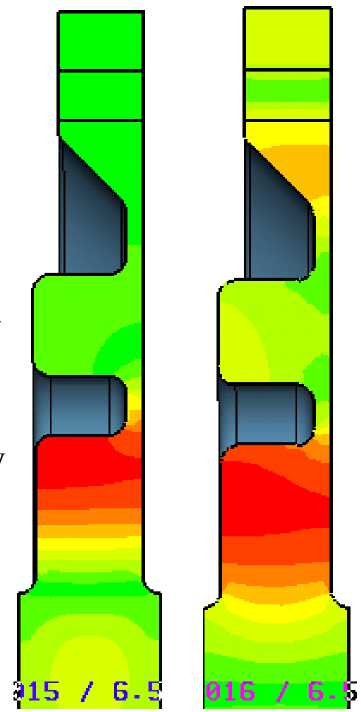
Phase advance

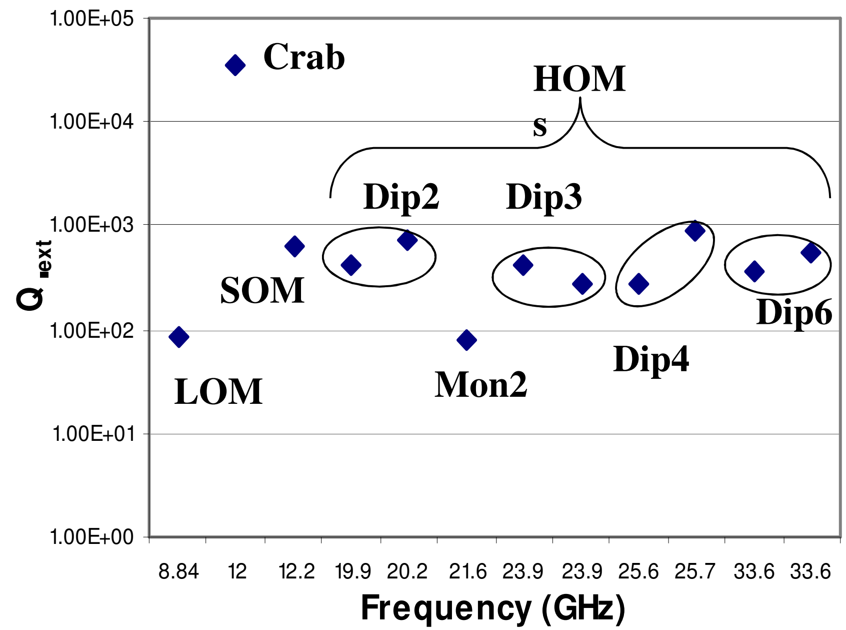


Choke Damping

- A study was performed of a choke mode damping structures for crab cavities.
- As the dipole mode has two polarisations we must damp one heavily without affecting the other.
- This proved difficult in practice and resulted in an asymmetric choke. These prove to be not as efficient as traditional choke mode structures.



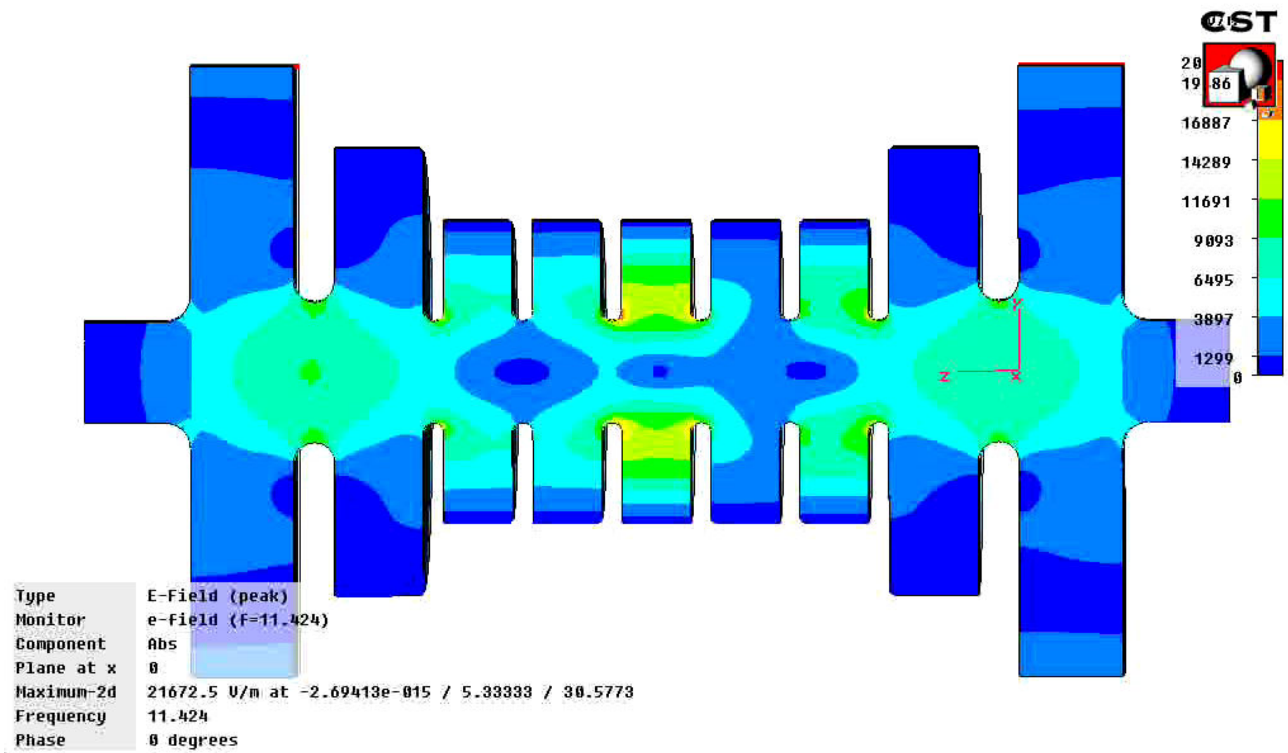




Gradient Testing

Figure showing peak electric field in a cavity being manufactured by Shakespeare Engineering in the UK. Test will be undertaken at SLAC to determine the maximum gradient for our structures.

A key feature of this cavity is that the end cells are excited in a “TE111 like mode” so that the maximum gradient occurs in the centre cells which have “TM110 like excitation”.



Cavity Under Construction