Cockcroft Institute

LANCASTER UNIVERSITY

Crab cavity development for CLIC

Contributors

Graeme Burt	CI/Lancaster University
Praveen Kumar Ambattu	CI/Lancaster University
Amos Dexter	CI/Lancaster University
Valery Dolgashev	SLAC

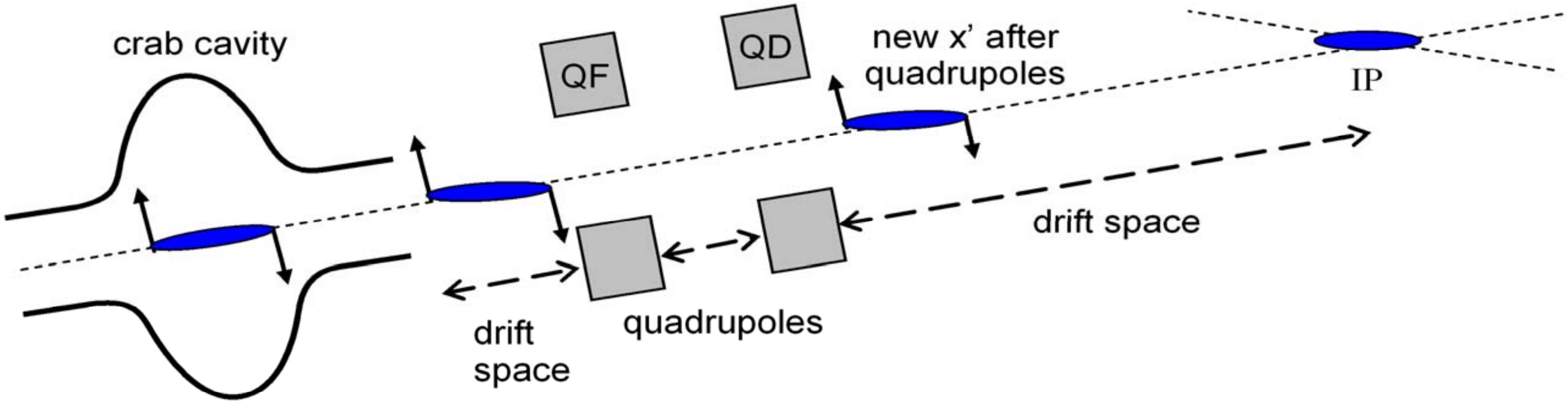
Other Collaborators

CERN	
ASTeC	Peter McIntosh
Manchester University	Roger Jones
SLAC	Sami Tantawi

Cockcroft Institute

LANCASTER UNIVERSITY

Crab Cavity Function



The crab cavity is a deflection cavity operated with a 90^{o} 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

Key Required Outcomes

1. Damp, measure and confirm the predicted wakes.

2. Establish feasible/achievable level of phase control performance. (Requirement is beyond state of the art)

Cockcroft Institute

LANCASTER UNIVERSITY

Cavity Requirement

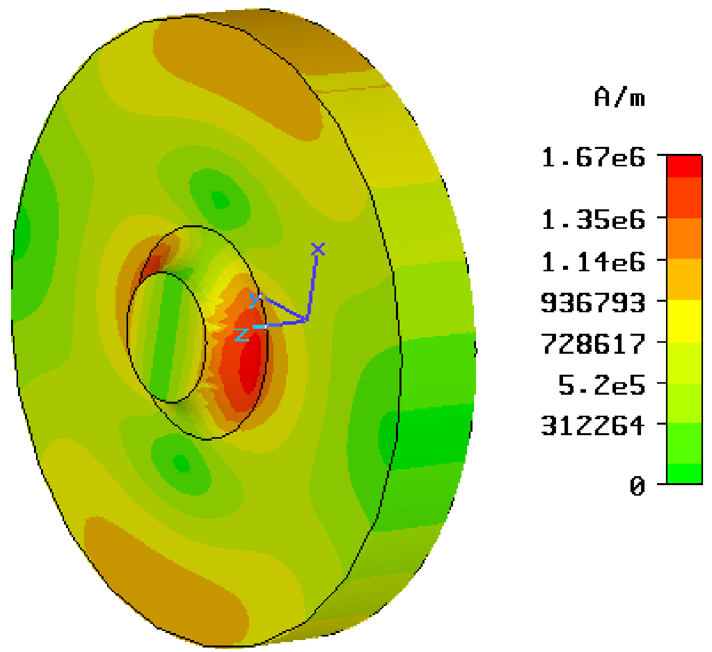
- If every sixth bucket filled frequency > 2.0 GHz
- Transverse & longitudinal space not a problem
- Short bunch structure suggests copper structure

Planned Approach

- Design 12 GHz damped detuned TW dipole cavity
- Compute wakefields
- If necessary scale to lower frequency for smaller kicks

Other Issues for a Copper Structure

- RF Source Power requirements
- Pulsed heating on the iris
- Gradient (limited by breakdown?)



Cockcroft Institute

Transverse Kick for 3 TeV CM

To minimise required cavity kick R12 needs to be large hence put the cavity close to IP (25 metres suggested)

For 20 mrad crossing and using as 12 GHz structure

$$V_{max} = \frac{\theta_r E_o c}{R_{12}\omega} = \frac{10^{-2} \times 1.5 \times 10^{12} \times 3 \times 10^{8}}{25 \times 2\pi \times 12 \times 10^{9}} = 2.4\text{MV}$$

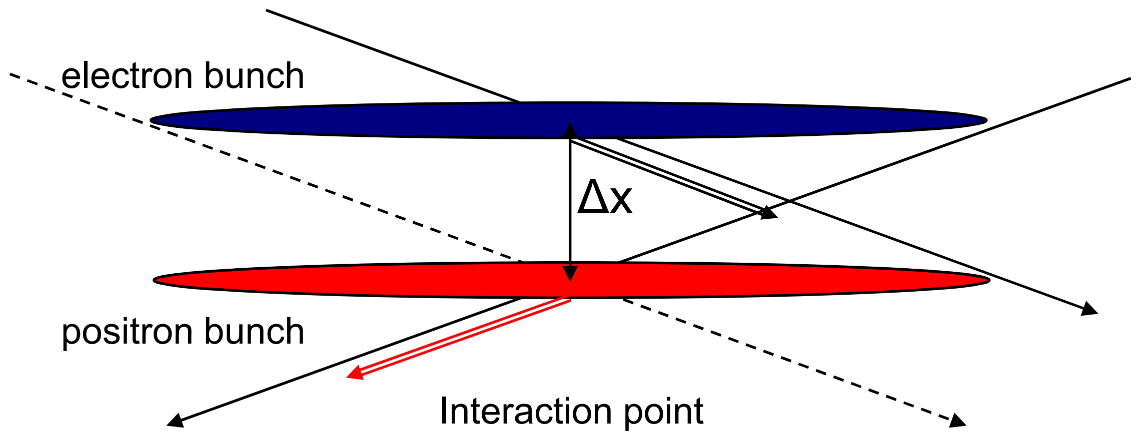
At 20 MV/m transverse gradient this is only 12 cm which is 10-15 cells depending on the cavity design.

This is about 3 MW RF for a SW design probably more for TW.

As vertical kicks caused by unwanted modes in the cavity are dangerous one would like R34 to be small.

Phase synchronisation requirement for no more than 2% luminosity loss

Crabbed crossing angle with phase jitter



Luminosity reduction factor S is given as

$$S = \exp\left(-\frac{\Delta x^2}{4\sigma_x^{\ 2}}\right)$$

and

$$\Delta x = \frac{c\,\theta_r \sin(\Delta\varphi)}{\omega}$$

	Phase error (degrees)	
Crossing angle	12 GHz	30 GHz
20 mrad	0.02	0.06

Initial assessment

- Without making the wakefield calculation, the crab cavity dimensions can't be finalised

- However, bigger irises can be preferred for possible wakefield suppression.

- For efficient heat transfer, the iris should be of sufficient thickness but not too much to lower the cavity Q .

- Standing wave cavities have much higher shunt impedance and lower surface fields for dipole modes. But if we use the pi mode we have low cavity coupling (nearby modes an issue).

- Travelling wave cavities have a large separation of nearby modes, but will require more power and have higher fields.

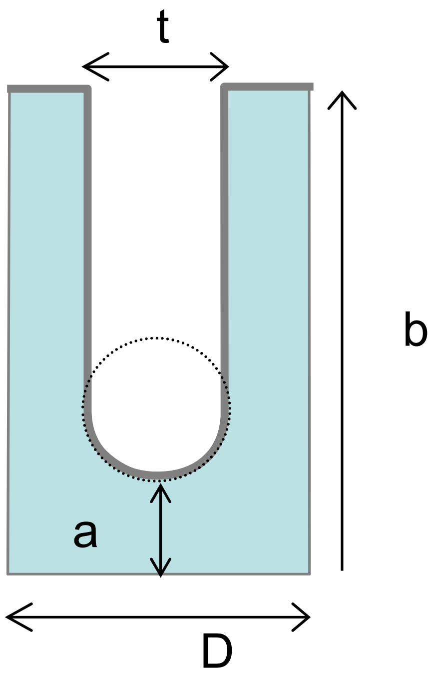
Cockcroft Institute

LANCASTER UNIVERSITY

Short study of infinitely periodic coupled dipole cavities

- Electromagnetic simulation tool is CST Microwave studio
- The structure used is a single cell cavity with periodic boundary condition enforced at either ends
- Structures are taken to be copper
- Figures of merit such as the quality factor, R/Q , peak fields and group velocity/ cavity coupling are simulated and compared for various cavity dimensions giving the first dipole frequency at 12 GHz and for various phase advance/cell (2π/3, 5π/6 and π radians)

The cavity cell structure



Periodic boundary conditions

D	**Cell length**
t	**Iris thickness**
t/2	**Iris curvature**
b	**Equator radius**
a	**Iris radius**

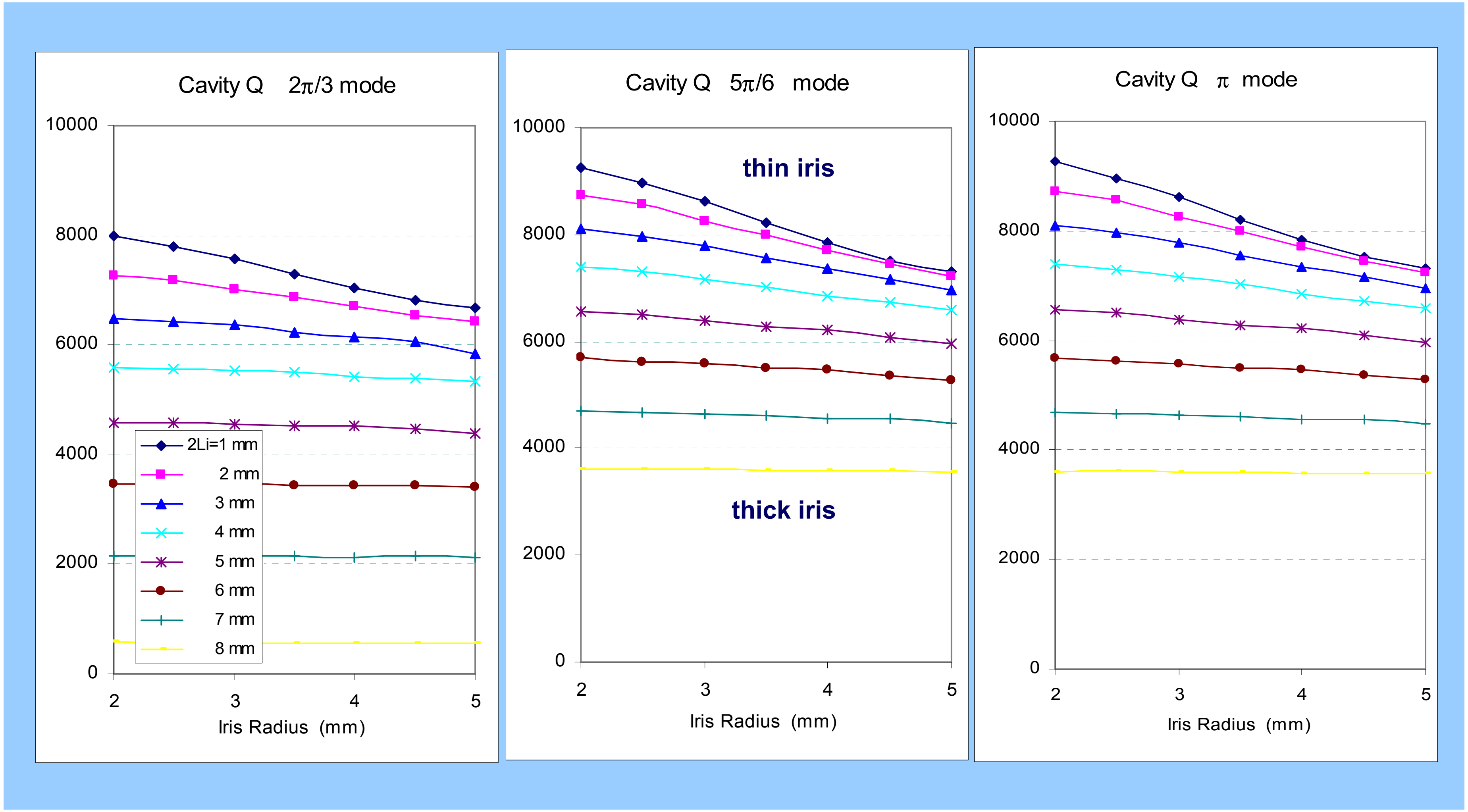
Phase advance per cell, φ radians	**Length of the cell, D mm (11.994 GHz)**
2π/3 (TW)	8.332
5π/6 (TW)	10.415
π (SW)	12.498

Four independent cell parameters –
but one fixed by frequency and one fixed by phase advance
hence investigative plots only vary iris thickness and iris radius

Q vs iris radius and thickness

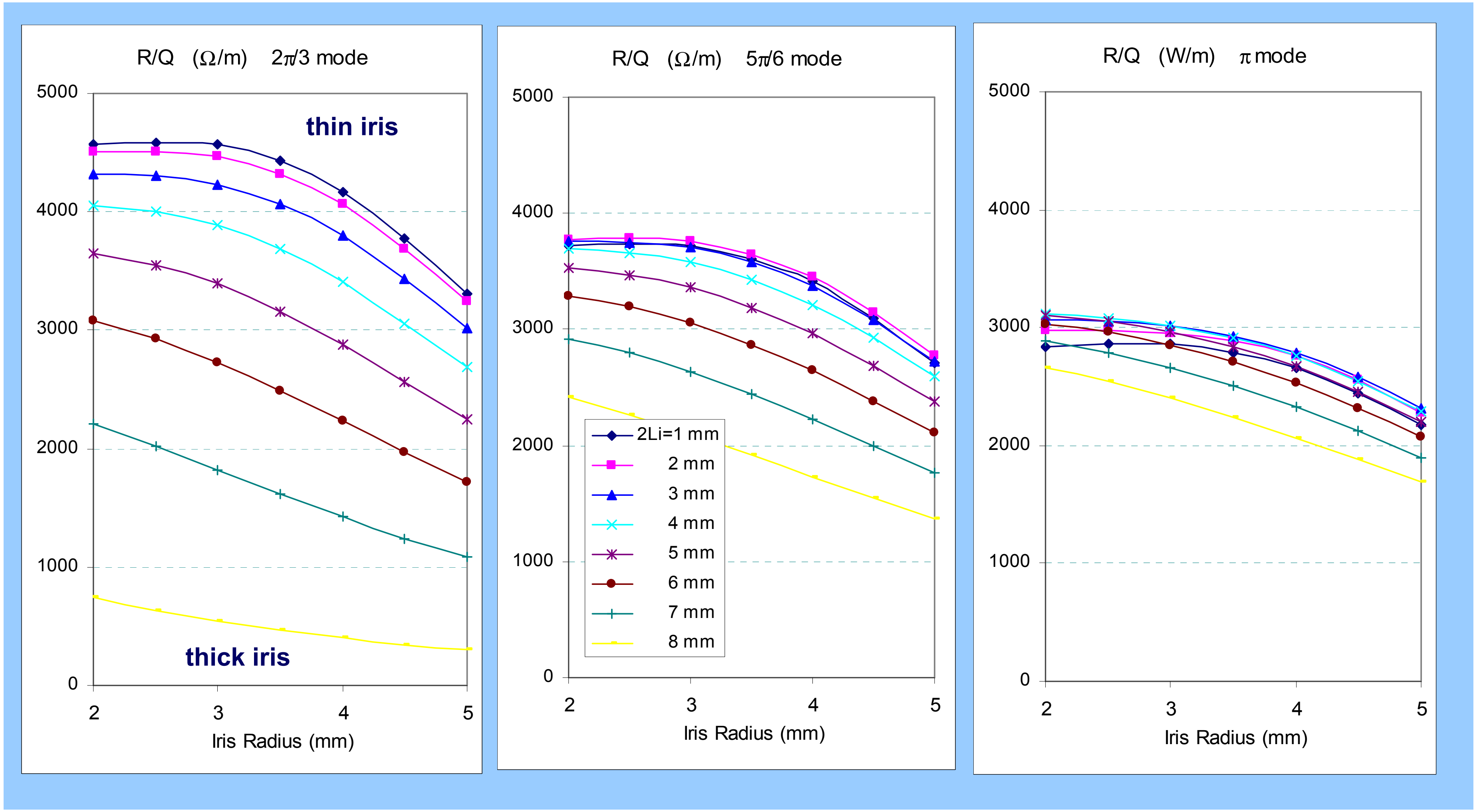
Cockcroft Institute

LANCASTER UNIVERSITY



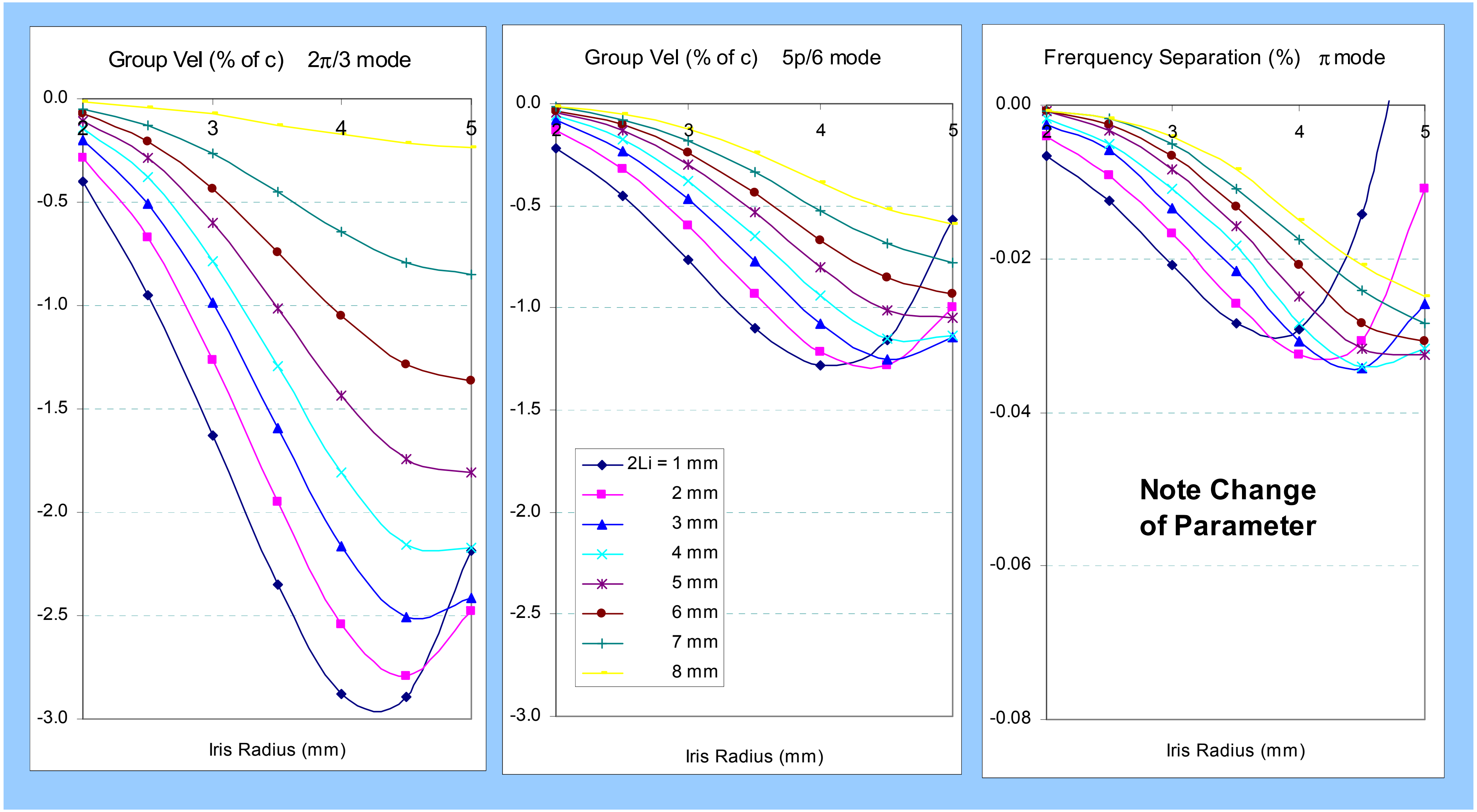
Lines labelled in key correspond to differing iris thicknesses, 2 - 3 mm is preferred
x-axis gives iris radius, 4 mm or above is preferred

R/Q vs iris radius and thickness



Lines labelled in key correspond to differing iris thicknesses, 2 - 3 mm is preferred
x-axis gives iris radius, 4 mm or above is preferred

Group vel. vs iris radius and thickness

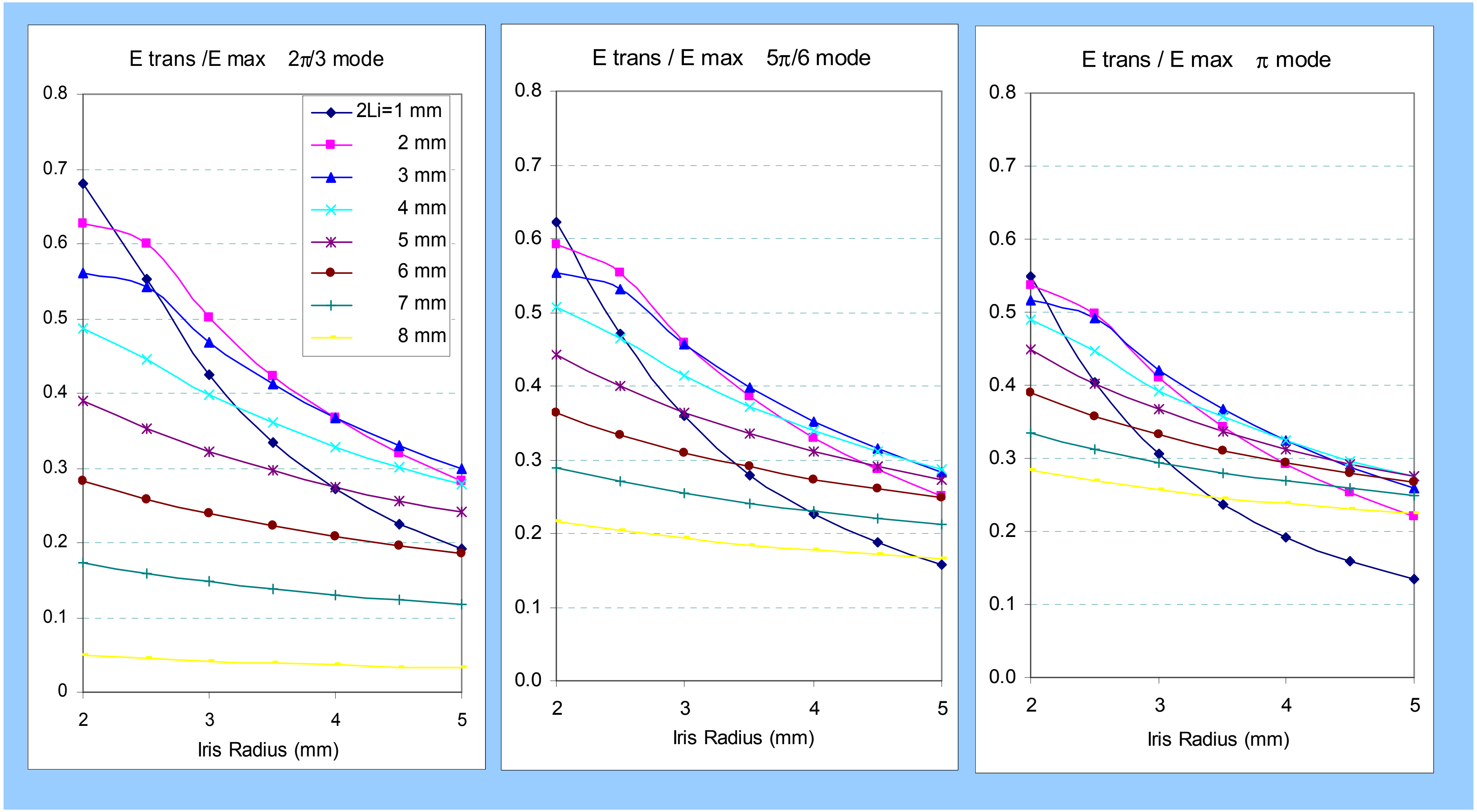


Lines labelled in key correspond to differing iris thicknesses, 2 - 3 mm is preferred
x-axis gives iris radius, 4 mm or above is preferred

Cockcroft Institute

LANCASTER UNIVERSITY

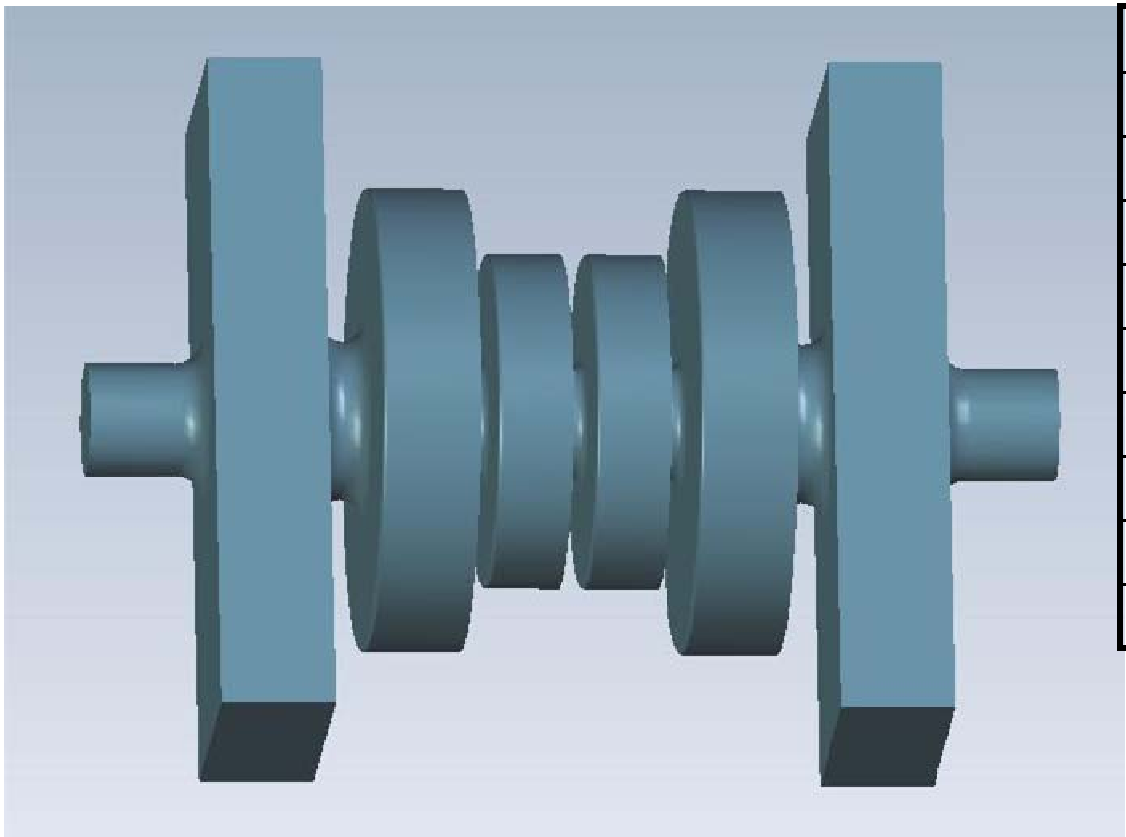
E trans/E max vs iris radius and thickness



Lines labelled in key correspond to differing iris thicknesses, 2 - 3 mm is preferred
x-axis gives iris radius, 4 mm or above is preferred

Design for SLAC Gradient Tests

Rectangular waveguide matched to TE111 like mode in first cells which match to TM110 like mode in centre cells (only two shown but plan to use three)



frequency	11.424 GHz
phase adv. per cell	120^{o}
mid cell mode	~ TM110
mid cell lengths	8.747 mm
iris mid cell radius	4.00 mm
iris thickness	2.390 mm
mid cell dia.	28.986 mm
end cell mode	~ TE111
end cell dia.	41.180 mm

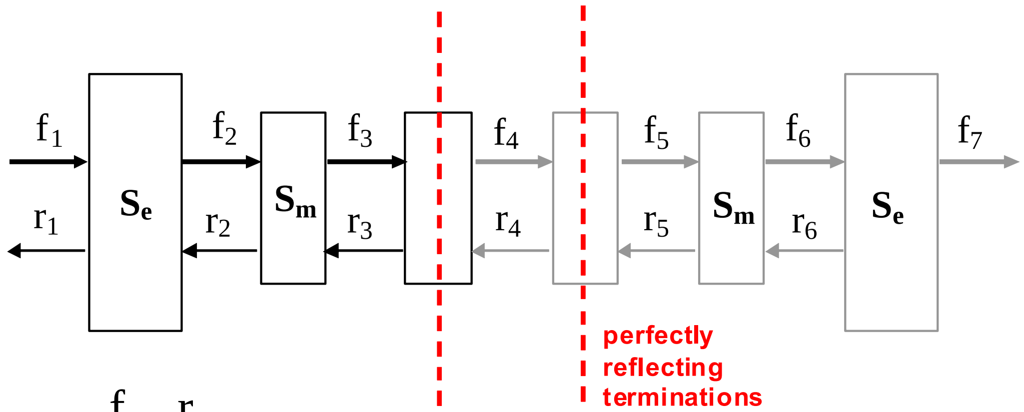
Picture shows internal volume from MWS simulation

Cockcroft Institute

Matching Technique

LANCASTER UNIVERSITY

Use procedure of Alesini D., Gallo A., Spataro B., Marinelli A. & Palumbo L. (Frascati)
Nuclear Instruments and methods in physics research A 580 (2007) 1176-1183



For a matched lossless structure admitting just a forward wave with fixed phase advance ϕ per cell we must have

$$r_1 = r_2 = r_3 = r_4 = r_5 = r_6 = 0$$

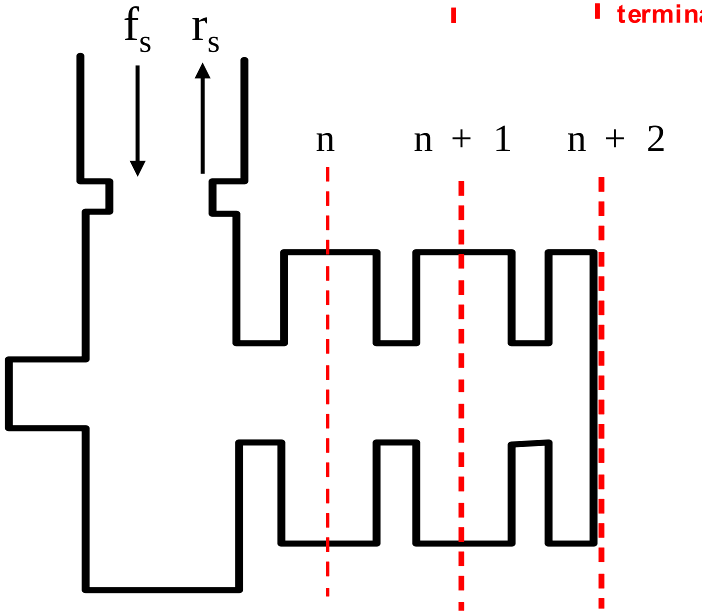
implies

$$S_e(1,1) = S_e(2,2) = S_m(1,1) = S_m(2,2) = 0$$

$$\frac{r_1}{f_1} = \Gamma_c \qquad \frac{r_s}{f_s} = \Gamma_s$$

ϕ = phase advance per cell

if $\frac{\Gamma_s(n+1)}{\Gamma_s(n)} = \frac{\Gamma_s(n+2)}{\Gamma_s(n+1)} = e^{-j2\phi}$ then $S_e(1,1) = 0$



Simulate real lossless structure with cut planes

Hence plot ratio of reflection coefs for structures shorted at n and n+1 as function of two matching cell parameters and interpolate to find parameters giving correct phase advance with no attenuation.

Floquet Theorem

- Used Floquet theorem to fine tune the structure.

Christopher Nantista, Sami Tantawi, and Valery Dolgashev, Low-field accelerator structure couplers and design techniques, Phys. Rev. ST Accel. Beams 7, 072001 (2004)

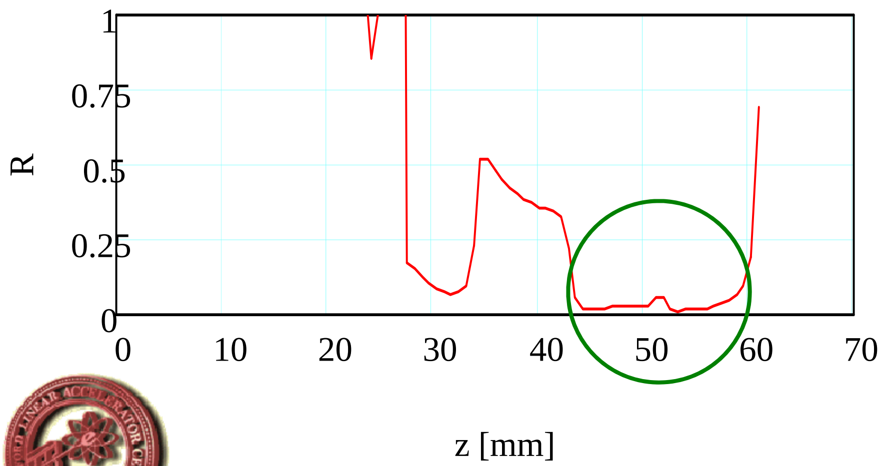
$$\Delta(z) = \frac{E(z+P) - E(z-P)}{E(z)}$$

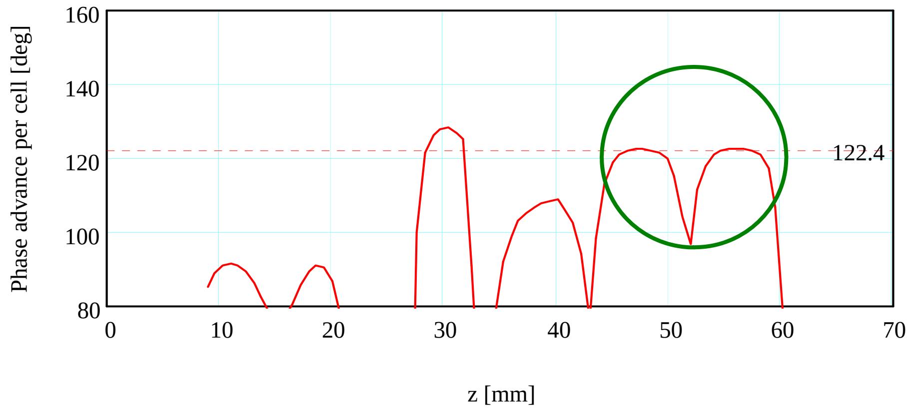
$$\Sigma(z) = \frac{E(z+P) + E(z-P)}{E(z)}$$

E = field
P = cell length
R = reflection coefficient
ψ = required phase advance

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

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





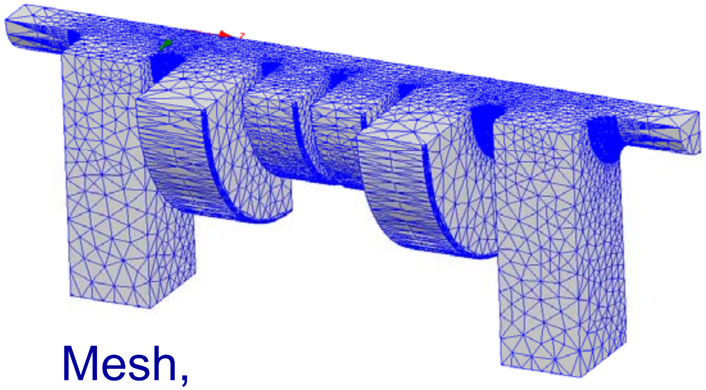
Cockcroft Institute

HFSS simulation – Electric Field

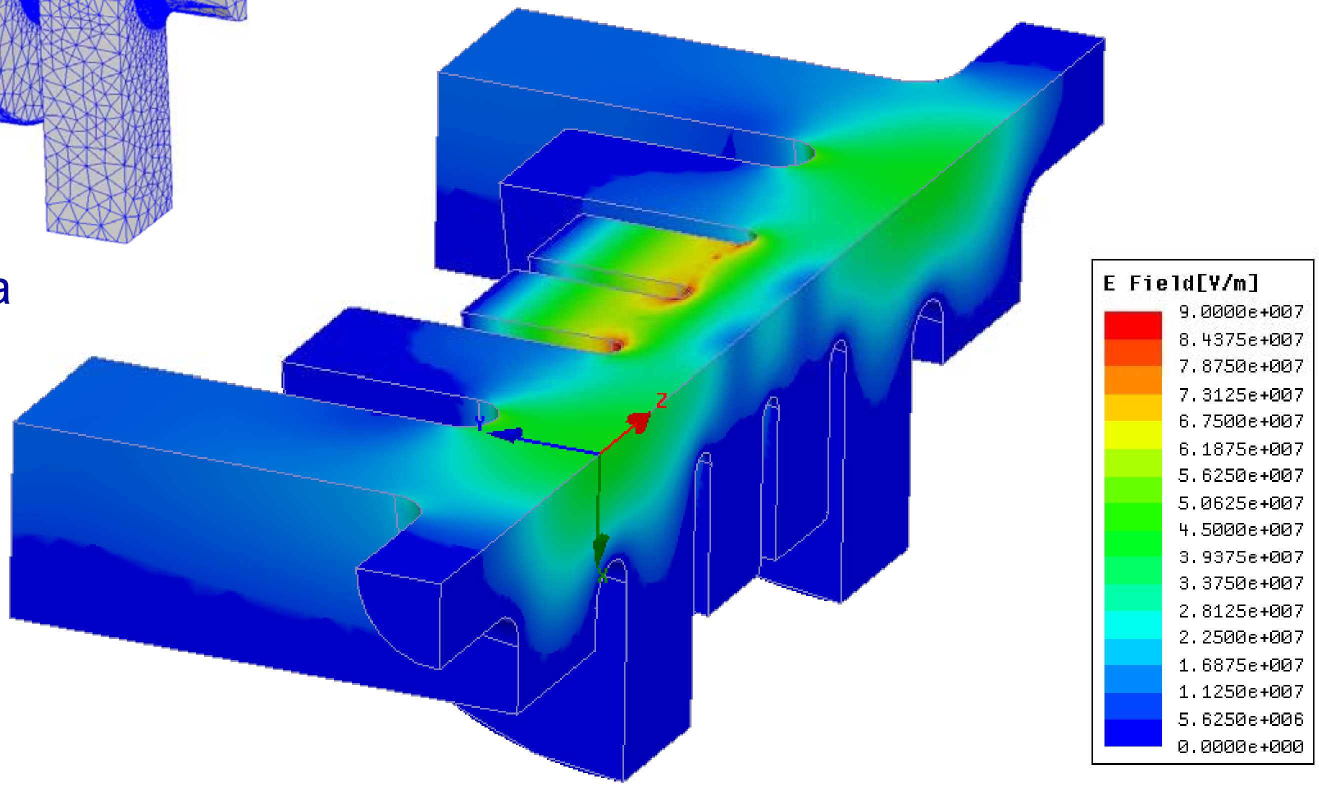
LANCASTER UNIVERSITY

11.424 GHz deflection mode,
20 MW transmitted power

Maximum
surface electric field
~90 MV/m



Mesh,
338,882 tetrahedra



Cockcroft Institute

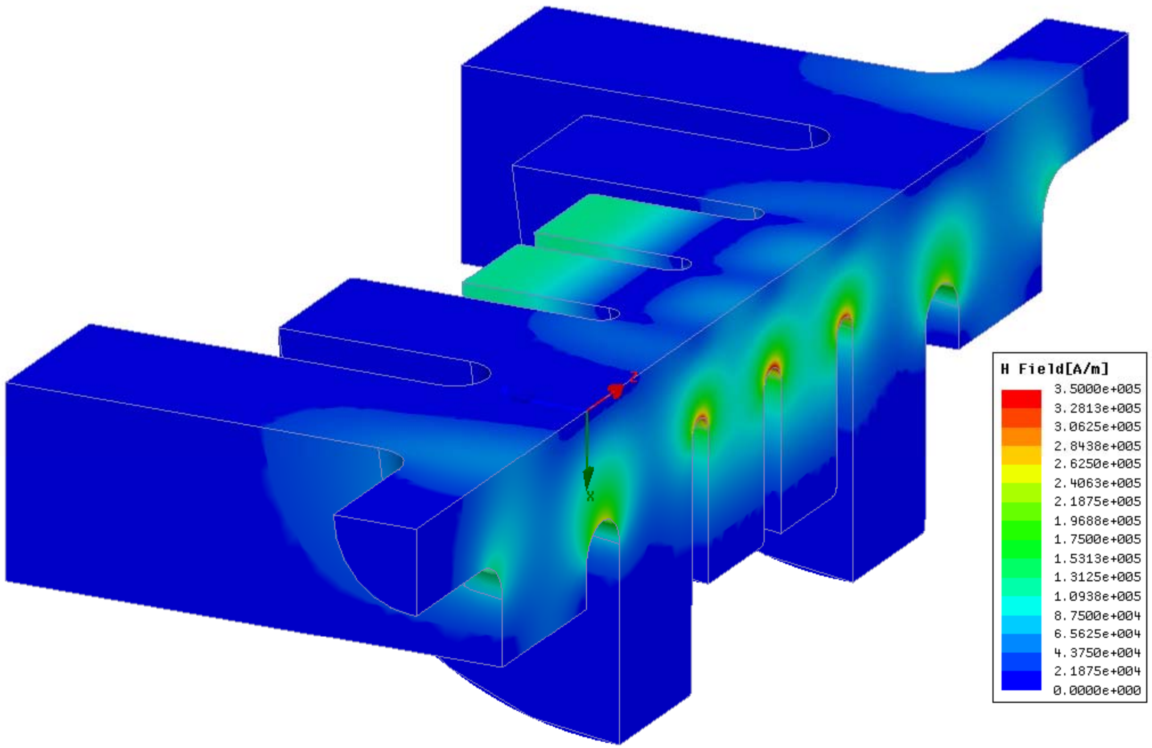
LANCASTER UNIVERSITY

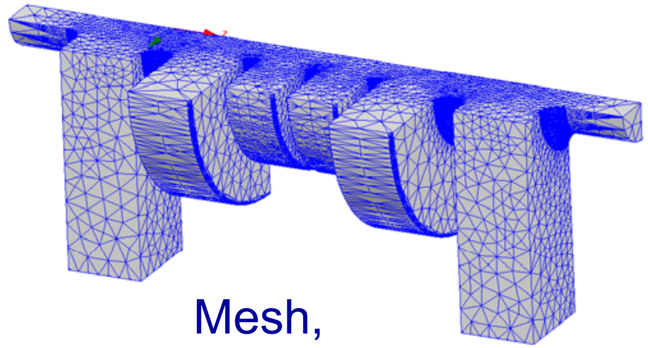
HFSS Simulation Magnetic Field

11.424 GHz deflection mode,
20 MW transmitted power

Maximum surface magnetic field ~350 kA/m

Pulse heating 24 deg. C for 200 ns pulse





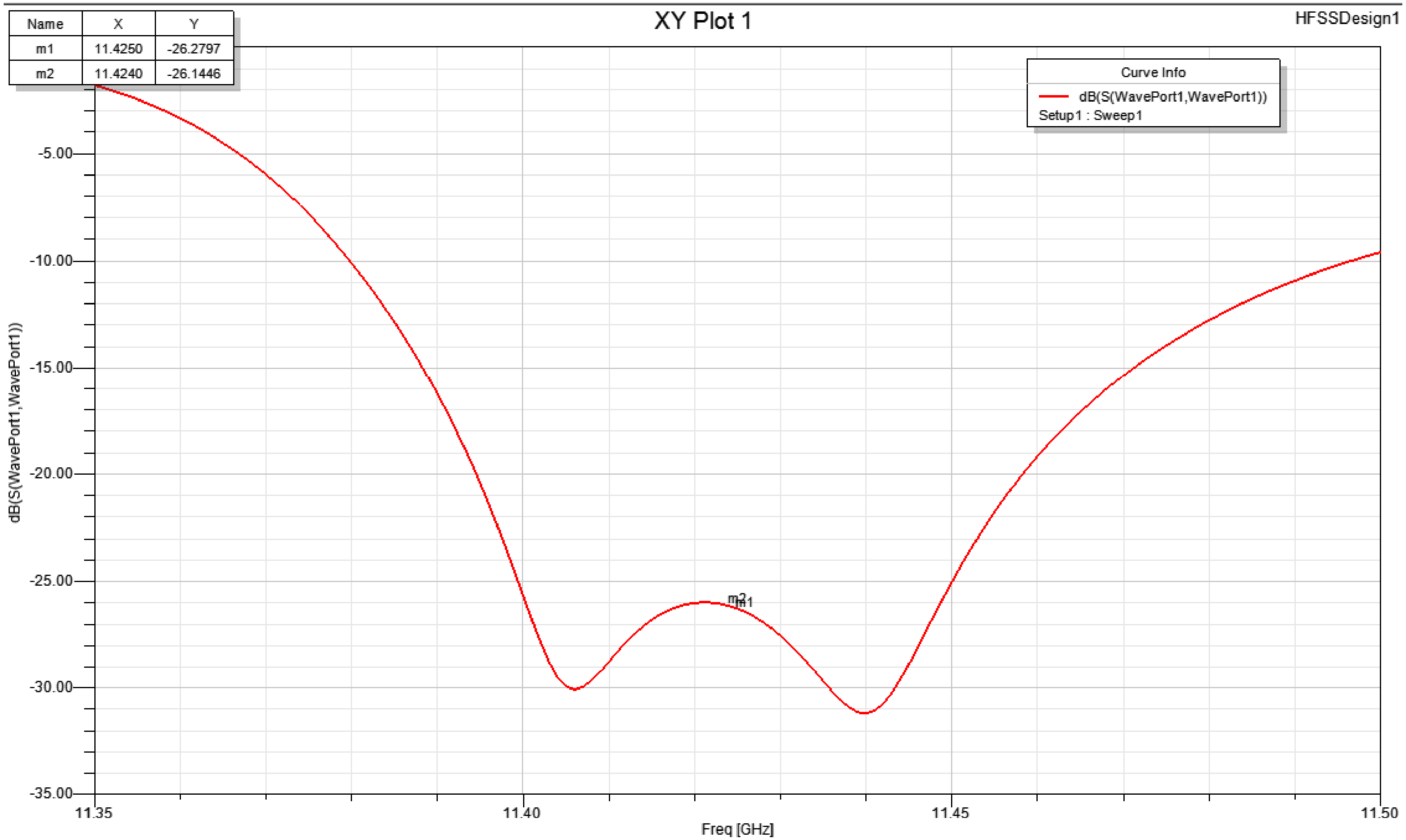
Mesh,
338,882
tetrahedra

Cockcroft Institute

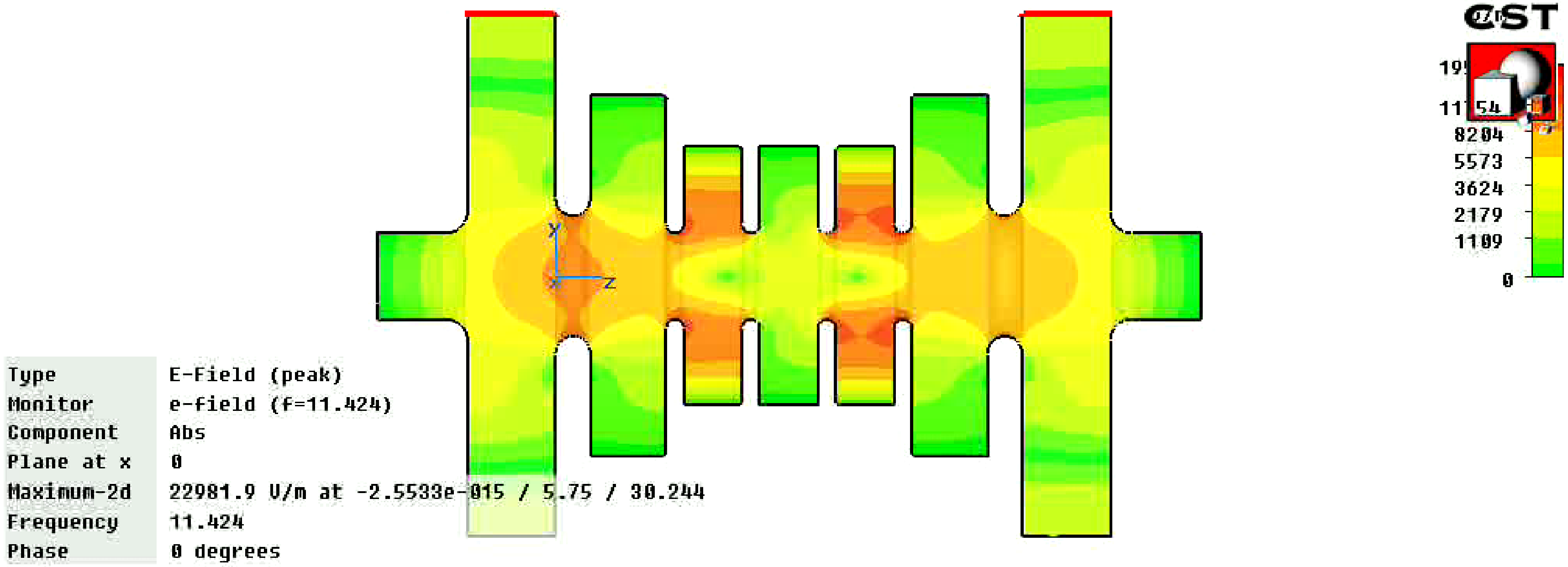
LANCASTER UNIVERSITY

Coupler Matching HFSS prediction

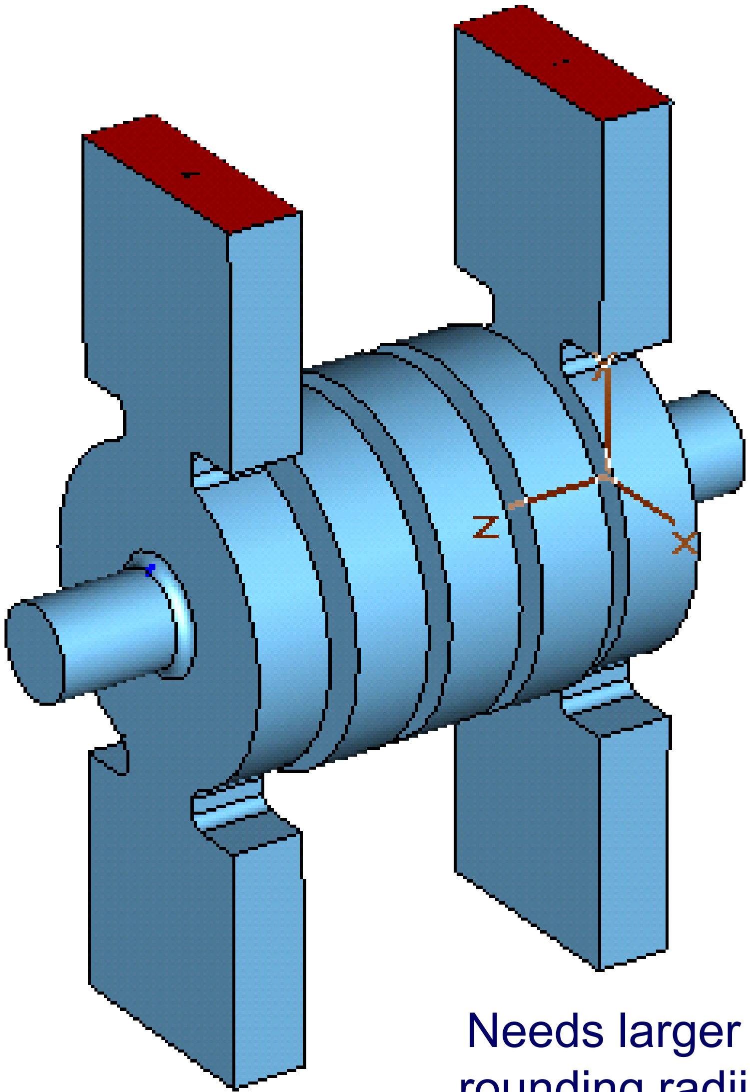
Name	X	Y
m1	11.4250	-26.2797
m2	11.4240	-26.1446



Travelling wave simulation

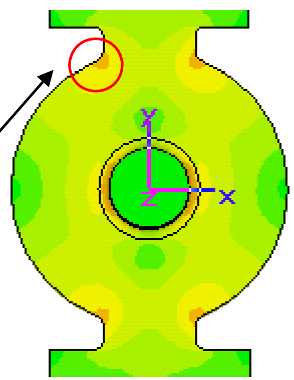


Coupler Design for CTF3 tests



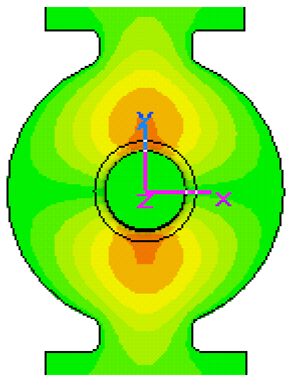
frequency	11.994 GHz
phase adv. per cell	120°
cell length	8.337 mm
Iris radius	4 mm
Iris thickness	2 mm
mid cell radius	14.457 mm
end cell radius	13.673 mm
coupling slot width	9.087mm
coupling slot thickness	2.275 mm

H end cell



Needs larger rounding radii

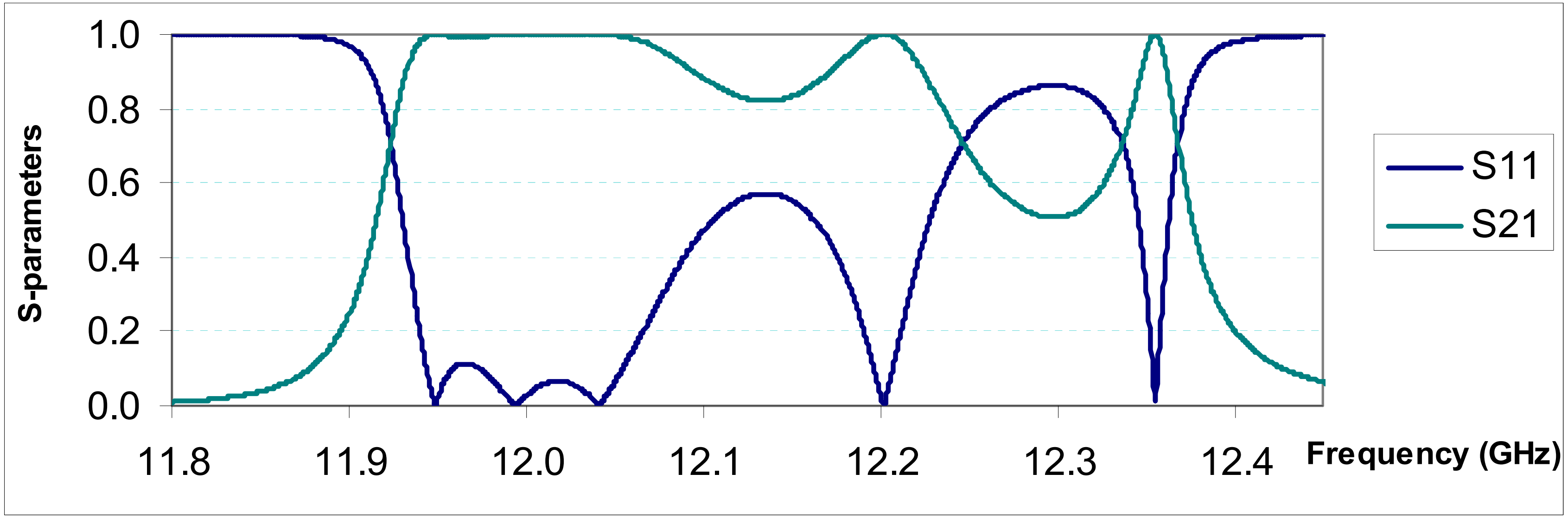
E end cell

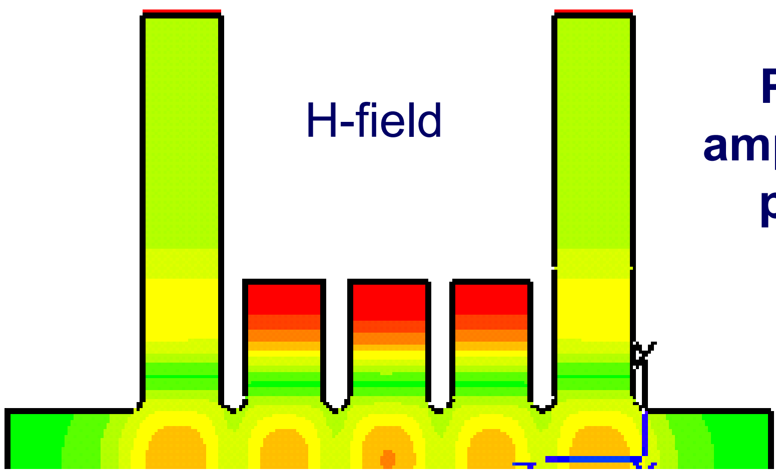


Cockcroft Institute

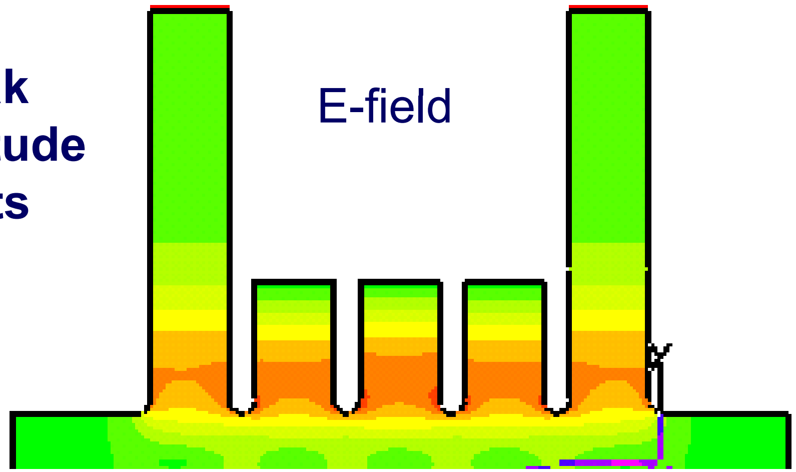
LANCASTER UNIVERSITY

S parameters & field uniformity for a matched TW





Peak amplitude plots



Only 5 cells are used in the simulations but final design will have more cells.

Cockcroft Institute

LANCASTER UNIVERSITY

Beam-loading Issues

- Beam-loading is typically large and depends on bunch offset
- Beam-loading might at worst vary randomly

Estimating voltage induced in crab cavity from one offset bunch
r_b ~ 0.5 mm (hopefully not this bad)
R/Q = 4000
$\phi = 0$
q = 0.6 nC
w = $2\pi \times 12$ GHz

$$\delta V_i = \frac{1}{2}\frac{r_b\omega}{c}\omega\left(\frac{R_d}{Q}\right) q\cos\phi$$

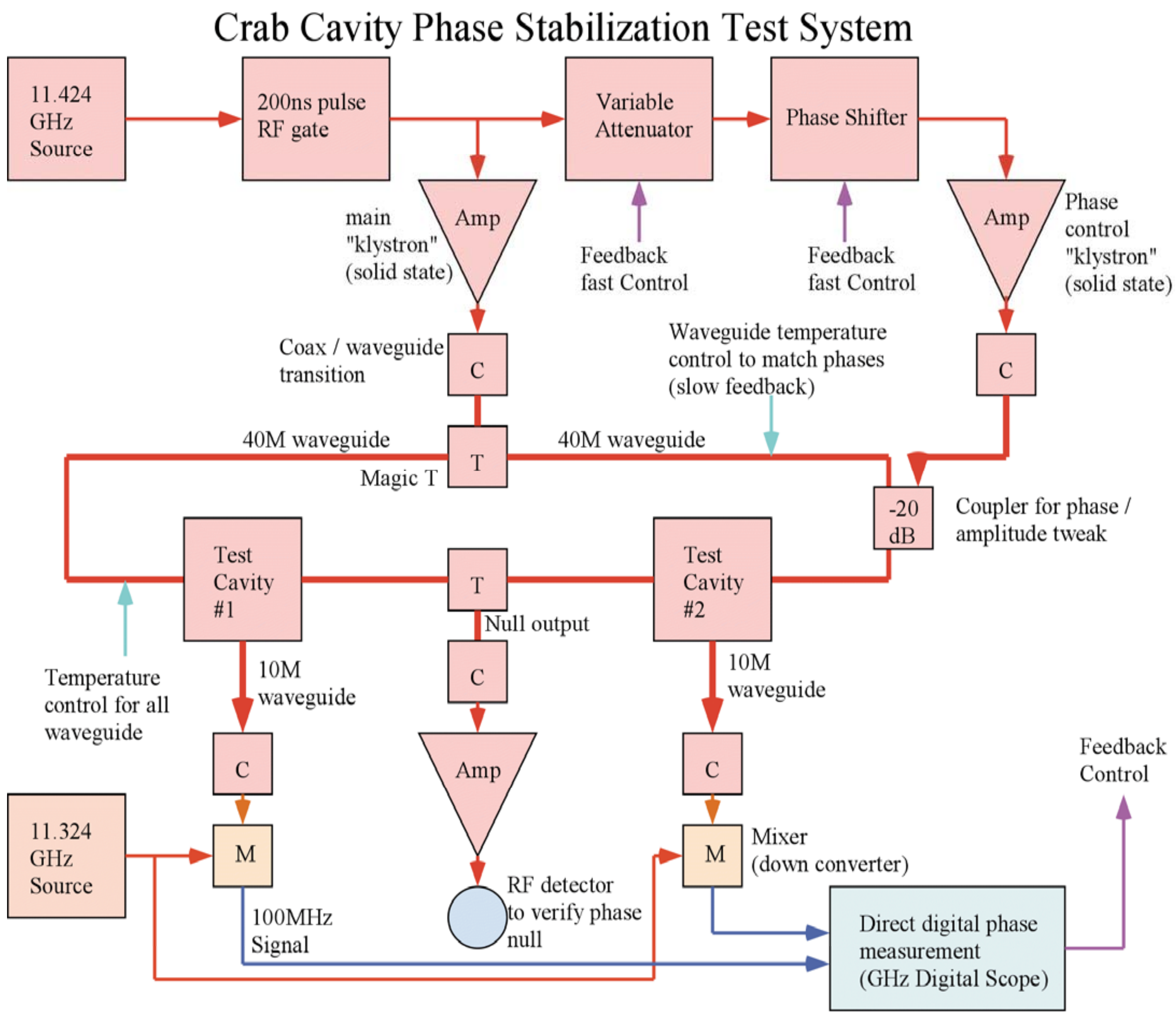
δV = 95 V
V = 2.4 MV / cells ~ 160 kV
hence 32 offset bunches could shift amplitude by 2%

Cockcroft Institute

Phase Control Issues

- Microphonics are insignificant for thick copper structures.
- Structure length is proportional to phase error hence need good temperature stability and central mounting.
- How much might beam-loading perturb phase in CLIC crab cavity? *(Expected to be small?)*
- Can travelling wave phase be determined accurately from the input phase or do unwanted modes, temperature and beam-loading give large uncertainties? *(If yes then only worry about source)*
- If unwanted modes, temperature stability and beam-loading not a problem the phase stability is determined by Klystron or PET structure hence must drive cavities on opposing beams with same device.

NLC phase synchronisation proposal



courtesy of J. Frisch

Cockcroft
Institute

Next Steps

- investigate maximum gradient vs. pulse length for X-band dipole structure at SLAC
- investigate pulse heating
- develop damped detuned structures.
- cooling requirements and mechanical design.
- determine likely phase and amplitude control performance for operation from a Klystron and from the PET structures.
- design beam test experiments.