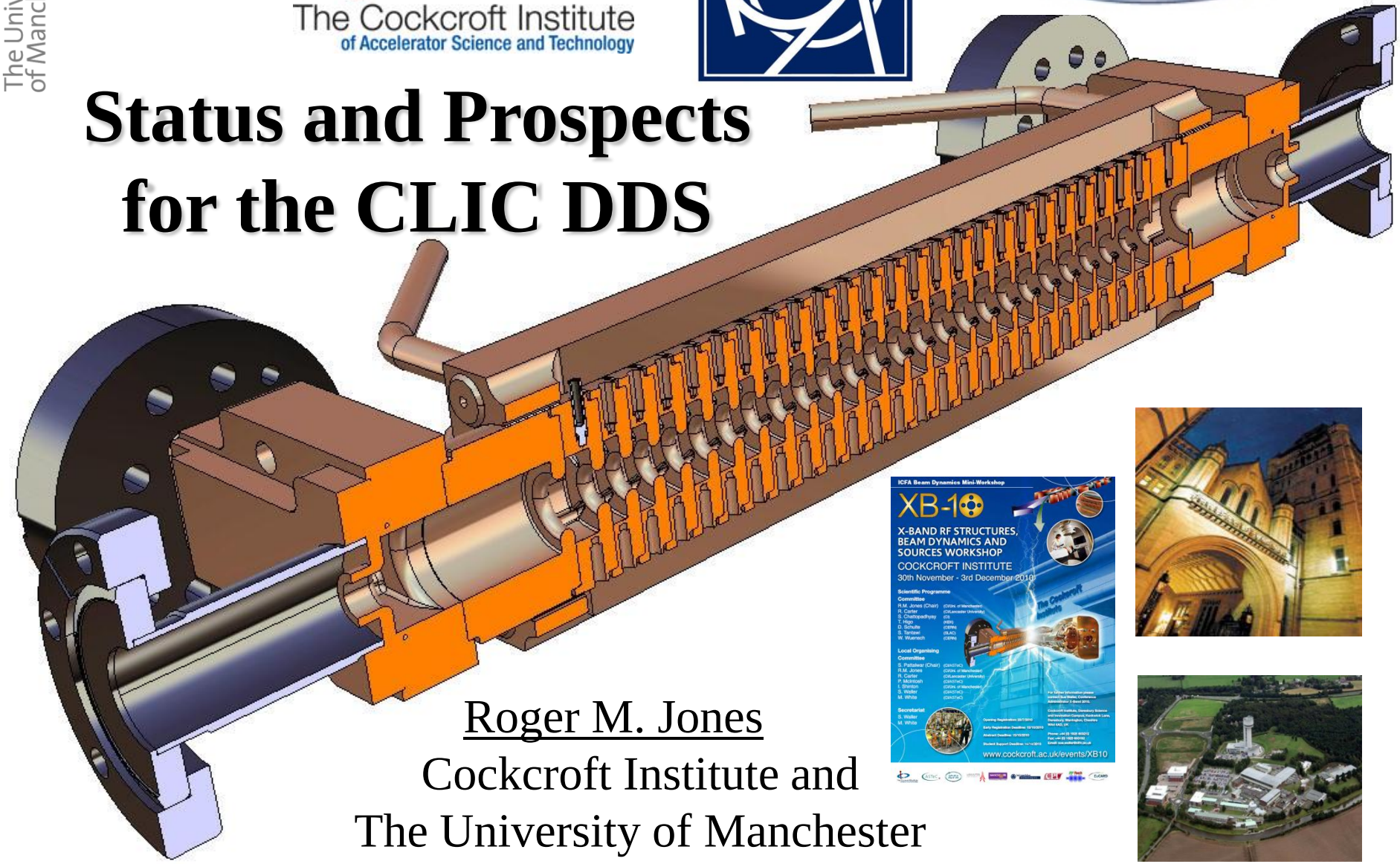
Status and Prospects for the CLIC DDS



Roger M. Jones
Cockcroft Institute and
The University of Manchester

Wake Function Suppression for CLIC -Staff

- Roger M. Jones (Univ. of Manchester faculty)
- Alessandro D'Elia (Dec 2008, Univ. of Manchester PDRA based at CERN)
- Vasim Khan (PhD student, Sept 2007)
- Nick Shipman (PhD student Sept 2010, largely focused on breakdown studies)
- Part of EuCARD (European Coordination for Accelerator Research and Development) FP7 NCLinac Task 9.2

V. Khan, CI/Univ. of Manchester Ph.D. student Finishing 2011!?

A. D'Elia, CI/Univ. of Manchester PDRA based at CERN (former CERN Fellow).

N. Shipman, NEW! CERN/CI/Univ. of Manchester Ph.D. student

- Major Collaborators: W. Wuensch, A. Grudiev, I. Syrachev, R. Zennaro, G. Riddone (CERN)

Overview

Three Main Parts:

1. ***Review of salient features of manifold damped and detuned linacs.***

2. ***Initial designs (three of them). ⇒ CLIC_DDS_C.***
3. ***Further surface field optimisations ⇒ CLIC_DDS_E(R).***
4. ***Finalisation of current design. Based on moderate damping on strong detuning. Single-structure based on the eight-fold interleaved for HP testing ⇒ CLIC_DDS_A***

5. **Concluding remarks and future plans.**

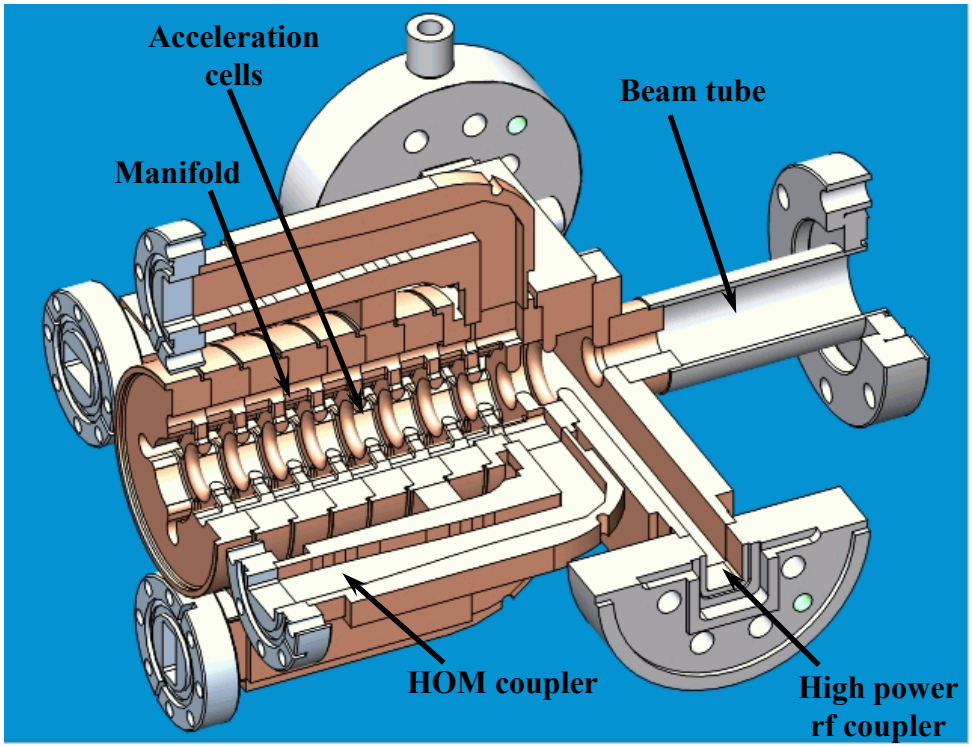
1. Introduction –Present CLIC baseline vs. alternate DDS design

- The present CLIC structure relies on linear tapering of cell parameters and heavy damping with a Q of ~10.
- Wake function suppression entails heavy damping through waveguides and dielectric damping materials in relatively close proximity to accelerating cells.
- Choke mode suppression provides an alternative, but may negatively impact R_{sh}

- **A viable alternative is presented by our CLIC_DDS design - parallels the DDS developed for the GLC/NLC, and entails:**

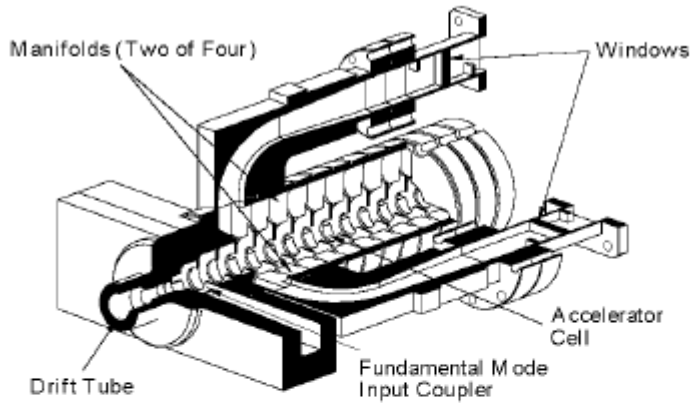
1. **Detuning the dipole bands by forcing the cell parameters to have a precise spread in the frequencies –presently Gaussian Kdn/df- and interleaving the frequencies of adjacent structures.**
2. **Moderate damping Q ~ 500-1000**

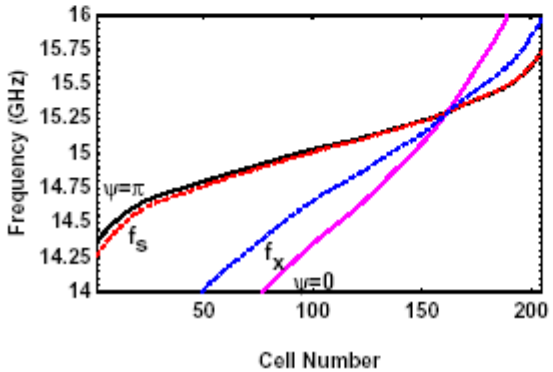
1. Features of CLIC DDS Accelerating Structure



- SLAC/KEK RDDS structure (left) illustrates the essential features of the conceptual design
- Each of the cells is tapered –iris reduces (with an erf-like distribution –although not unique)
- HOM manifold running alongside main structure removes dipole radiation and damps at remote location (4 in total)
- Each of the HOM manifolds can be instrumented to allow:
  1) Beam Position Monitoring
  2) Cell alignments to be inferred

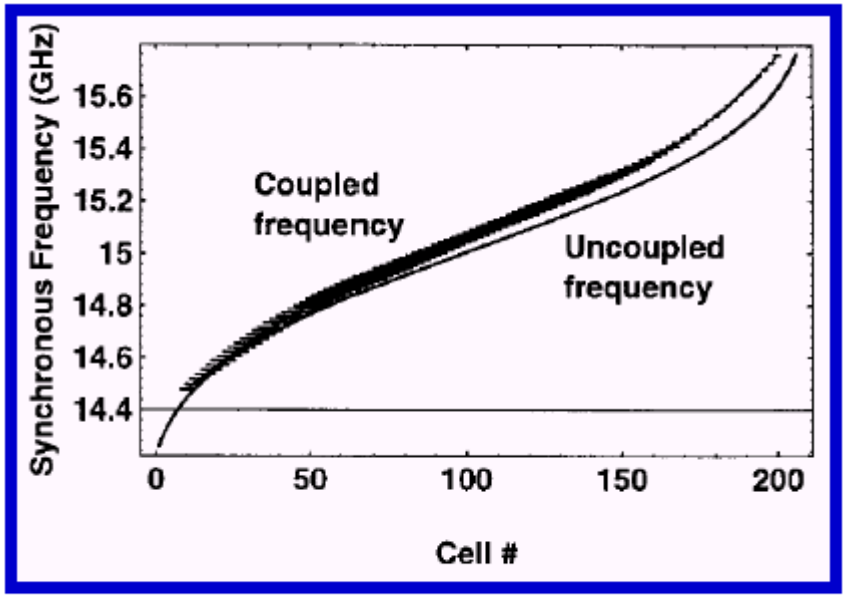
1. Features of DDS Accelerating Structure –GLC/NLC





- The manifold is a single mode TE_{10} and it is cut off to the accelerating mode (thus there is little impact on the accelerating mode)
- Each manifold is tapered to maintain good coupling
- RDDS has circular manifolds (superior pumping compared to rectangular guide).
- From mechanical considerations it is required to decouple 4 cells from either end of the structure.
- Detuned structure modes are localized standing waves with a spectrum of phase velocities.
- Both beam coupling and manifold coupling as functions of frequency are localized around particular cells.

1. Determination of Cell Offset From Energy Radiated Through Manifolds –GLC/NLC



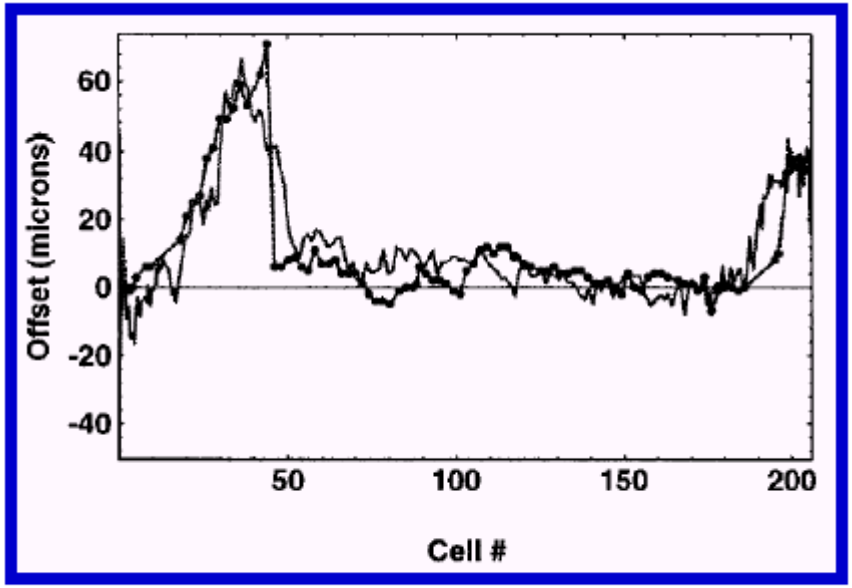
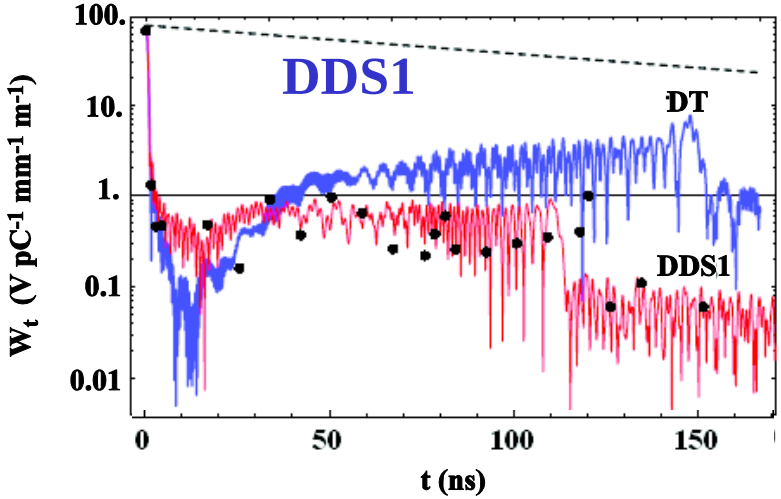


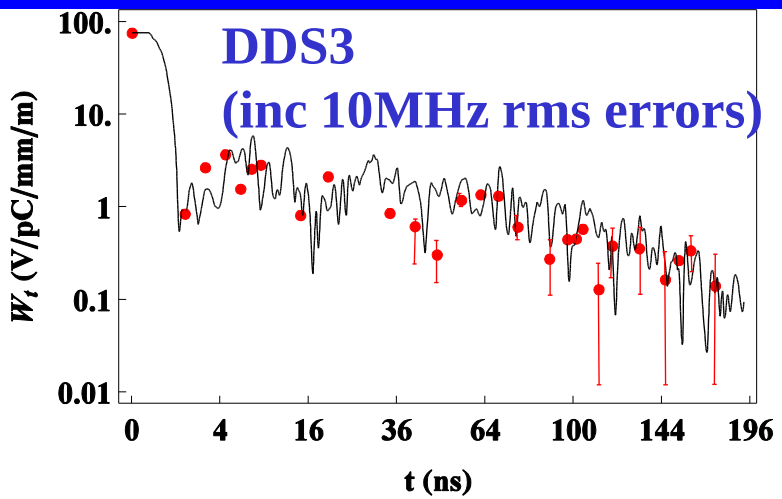
Illustration of the deviation of the synchronous frequency from the uncoupled one due to cell-to-cell detuning. The short horizontal lines indicate the extent to which cell offsets may be localized by frequency

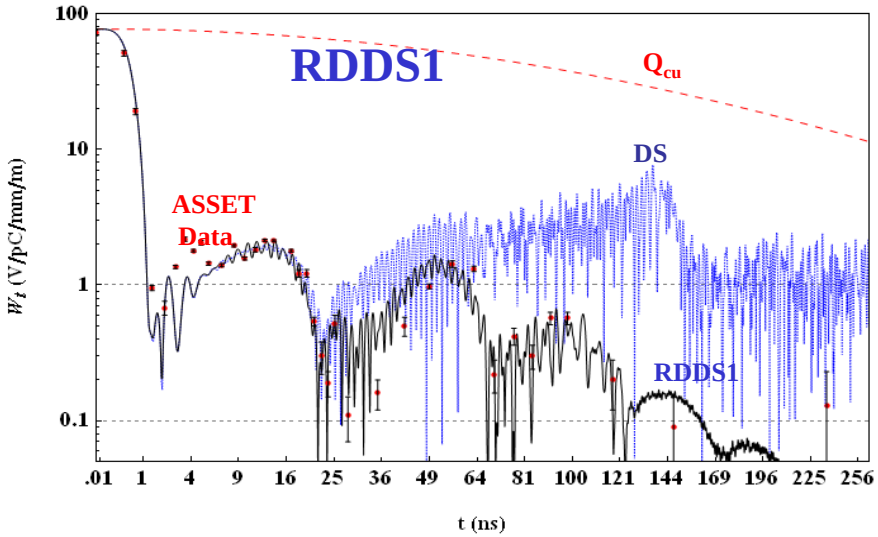
Comparison of the CMM (Coordinate Measuring Machine) data set versus the ASSET power minimization position data remapped from frequency to cell number for DDS1.

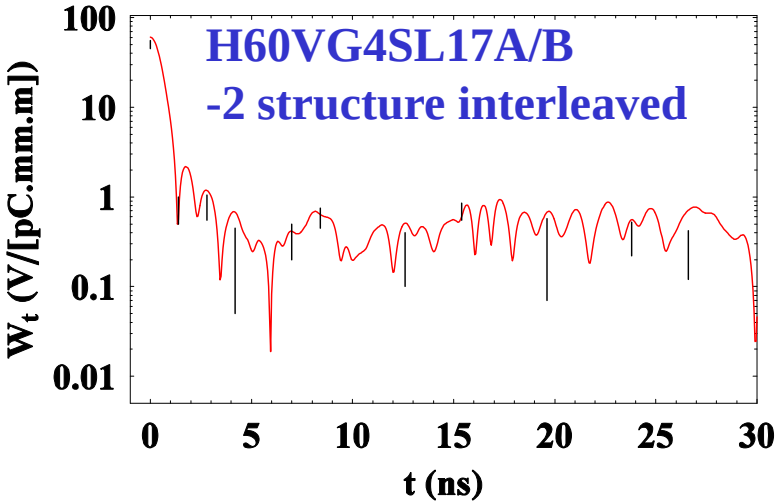
Dots indicate power minimisation

1. GLC/NLC Exp vs Cct Model Wake

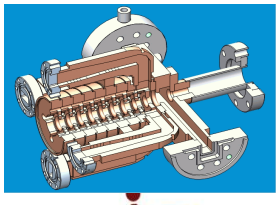








Conspectus of GLC/NLC Wake Function Prediction and Exp. Measurement (ASSET dots)



Refs: 1. R.M. Jones,et al, New J.Phys.11:033013,2009.
2. R.M. Jones et al., Phys.Rev.ST Accel. Beams 9:102001, 2006.
3. R.M. Jones, Phys.Rev.ST Accel. Beams, Oct.,2009.

1. CLIC Design Constraints

1) RF breakdown constraint

$$E_{sur}^{\max} < 260 MV/m$$

2) Pulsed surface temperature heating

$$\Delta T^{\max} < 56 K$$

3) Cost factor

$$P_{in}\sqrt[3]{\tau_p}\Big/C_{in} < 18 MW\sqrt[3]{ns}\Big/mm$$

Beam dynamics constraints

1) For a given structure, no. of particles per bunch N is decided by the <a>/λ and Δa/<a>

2) Maximum allowed wake on the first trailing bunch

$$W_{t1} \le \frac{6.667\times 4\times 10^9}{N}(V/[pC.mm.m])$$

Wake experienced by successive bunches must also be below this criterion

Grudiev and Wuensch, Design of an x-band accelerating structure for the CLIC main linacs, LINAC08

2.0 Initial CLIC_DDS Designs

Three designs

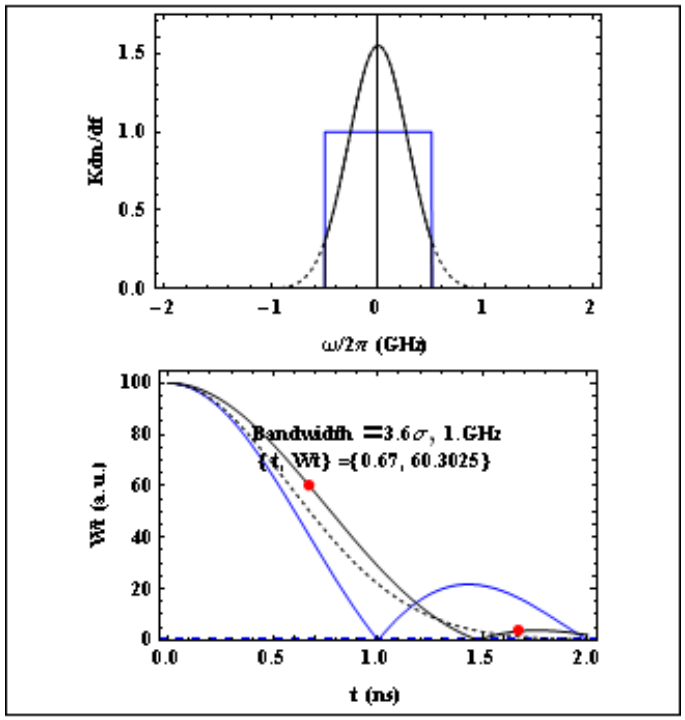
1. ~~Initial investigation of required bandwidth to damp all bunches (~3GHz) –succeeds to suppress wakes, fails breakdown criteria!~~

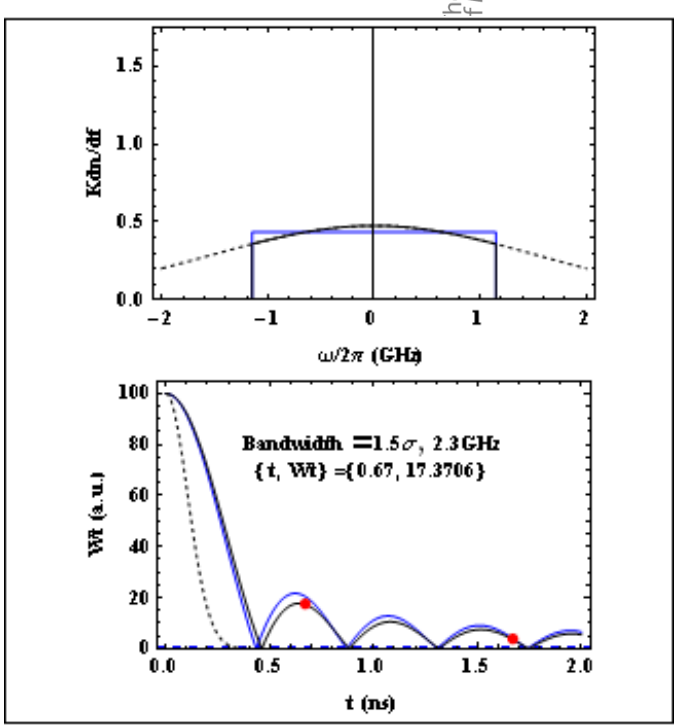
2. ~~New design, closely tied to CLIC_G (similar iris Δa), necessitates a bandwidth of ~ 1 GHz. Geometry modified to hit bunch zero crossings in the wakefield –succeeds from breakdown perspective, tight tolerances necessary to suppress wakes!~~

3. Relaxed parameters, modify bunch spacing from 6 to 8 rf cycles and modify bunch population. Wake well-suppressed and seems to satisfy surface field constraints. CLIC_DDS_C (Δf ~ 3.6σ, 13.75%) –SUCCESS (on suppressing wakes and meeting breakdown criteria)

2.1 Initial CLIC_DDS Design –Δf determination

Structure	CLIC _G
Frequency (GHz)	12
Avg. Iris radius/wavelength <a>/λ	0.11
Input / Output iris radii (mm)	3.15, 2.35
Input / Output iris thickness (mm)	1.67, 1.0
Group velocity (% c)	1.66, 0.83
No. of cells per cavity	24
Bunch separation (rf cycles)	6
No. of bunches in a train	312





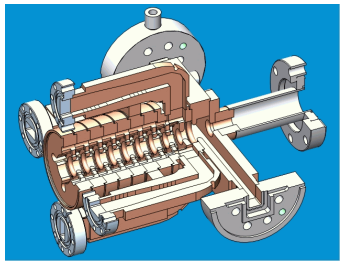
Bandwidth Variation

σ Variation

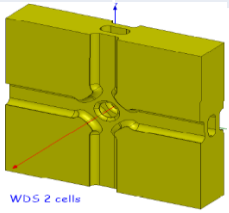
Truncated Gaussian :

$$W_t = 2\bar{K}e^{-2(\sigma\pi t)^2}\left|\chi(t,\Delta f)\right|$$

$$\text{where :}\quad \chi(t,\Delta f) = \frac{\mathrm{Re}\left\{\mathrm{erf}\left(\left[n_\sigma - 4i\pi\sigma t\right]/2\sqrt{2}\right)\right\}}{\mathrm{erf}\left(n_\sigma/2\sqrt{2}\right)}$$



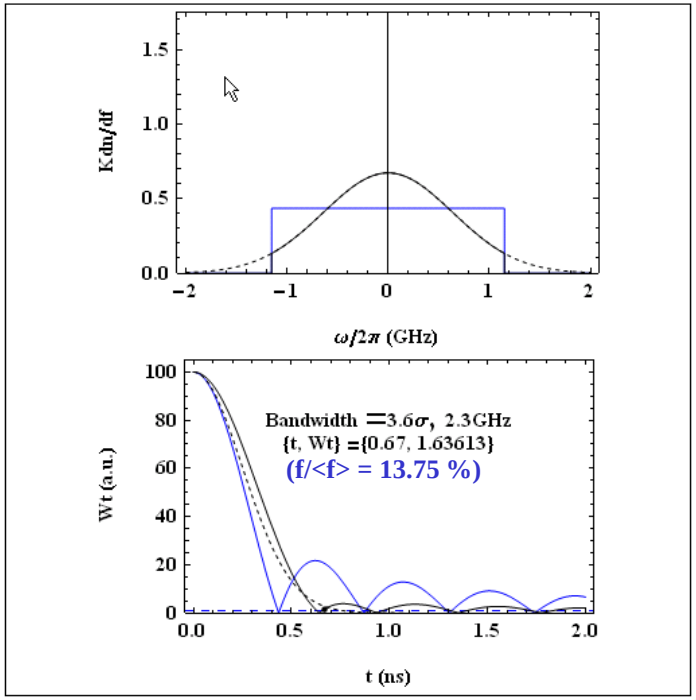
Lowest dipole
Δf ~ 1GHz
Q~ 10

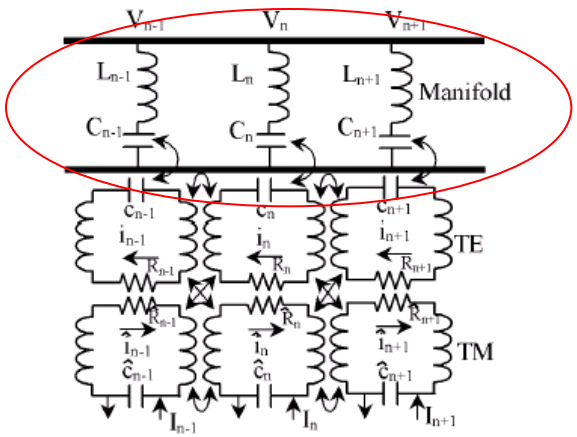


CLIC_G

⇒ CLIC_DDS Uncoupled Design

2.3 Relaxed parameters tied to surface field constraints





Three cells in the chain are illustrated. TM modes couple to the beam . Both TM and TE modes and excited and the coupling to the manifold is via TE modes. The manifold is modeled as a transmission line periodically loaded with L-C elements.

Uncoupled parameters

Cell 1

- Iris radius = 4.0 mm
- Iris thickness = 4.0 mm ,
- ellipticity = 1
- Q = 4771
- R'/Q = 11,640 Ω/m
- vg/c = 2.13 %c

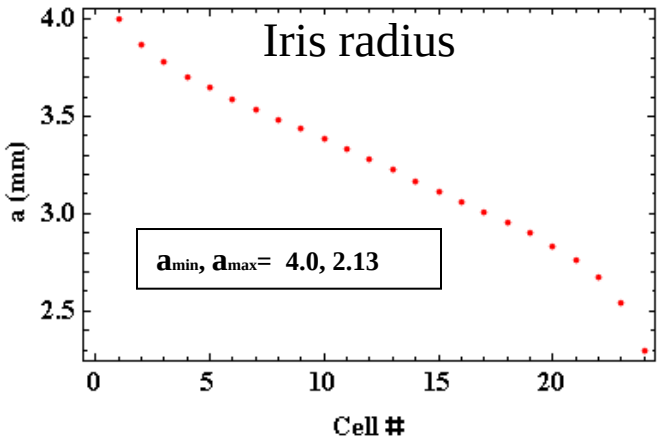
Cell 24

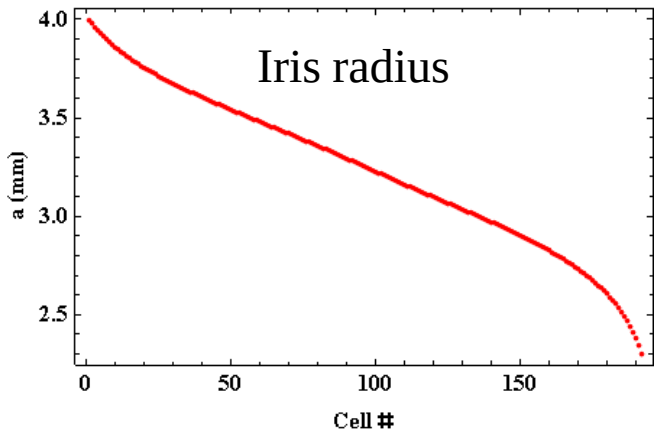
- Iris radius = 2.13 mm
- Iris thickness = 0.7 mm,
- ellipticity = 2
- Q = 6355
- R'/Q = 20,090 Ω/m
- vg/c = 0.9 %c

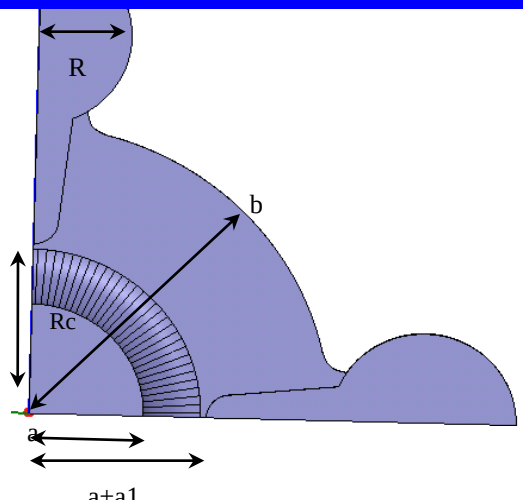
Cct Model Including Manifold-Coupling

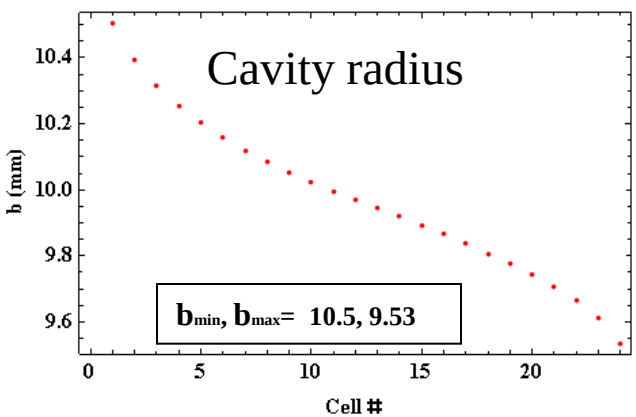
➢ **Employed spectral function and cct model, including Manifold-Coupling, to calculate overall wakefunction.**

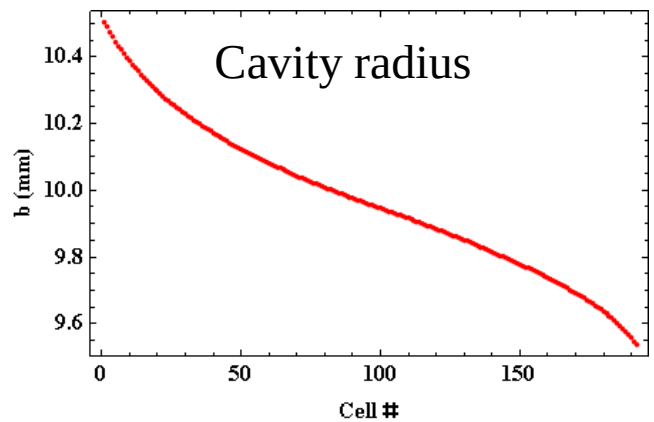
2.3 Structure Geometry: Cell Parameters

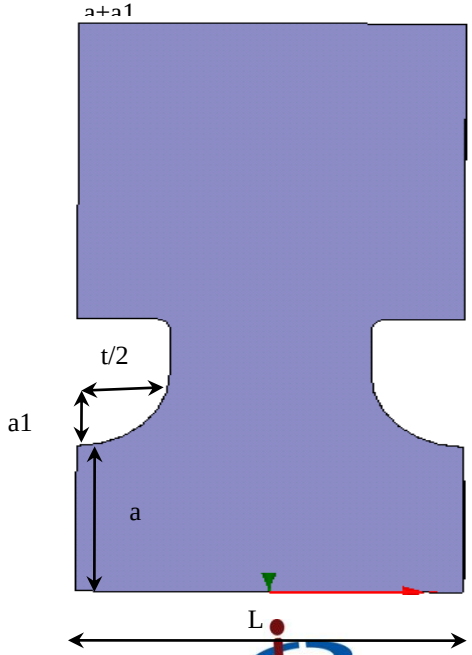








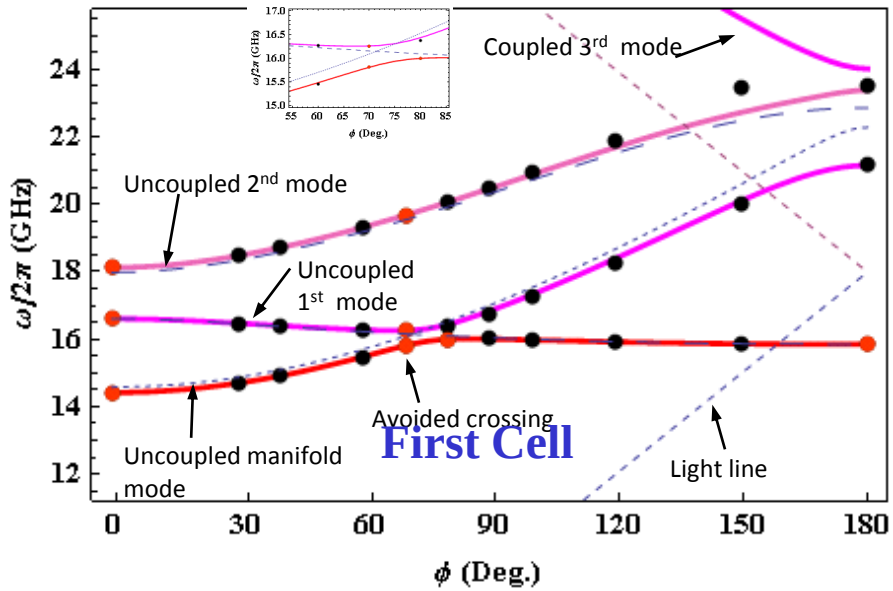


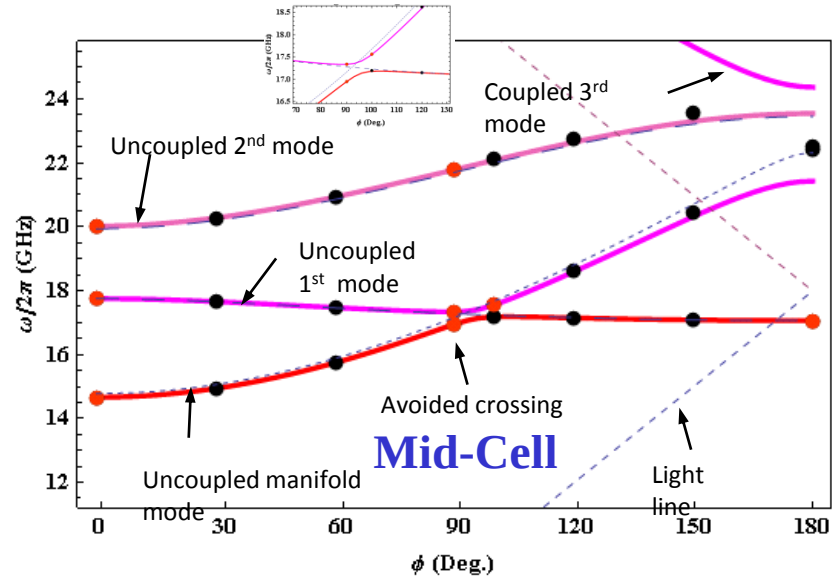


Sparse Sampled HPT (High Power Test)

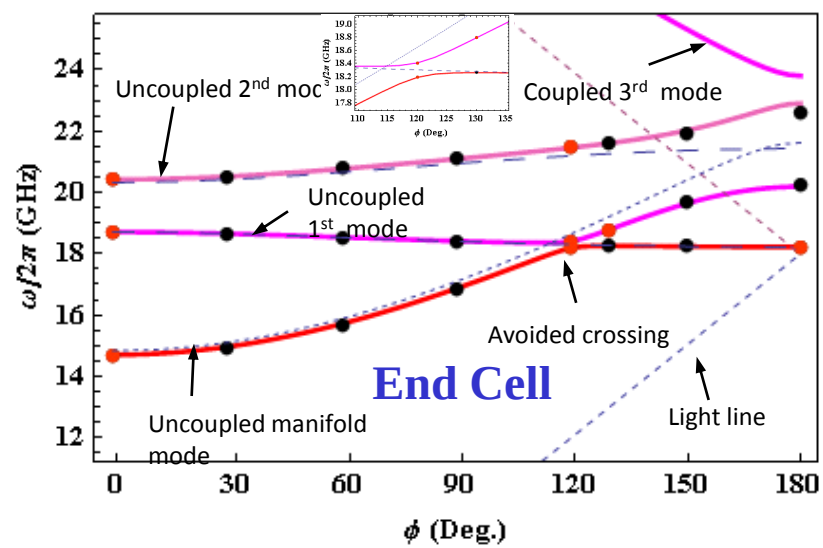
Fully Interleaved 8-structures

2.3 Relaxed parameters –full cct model

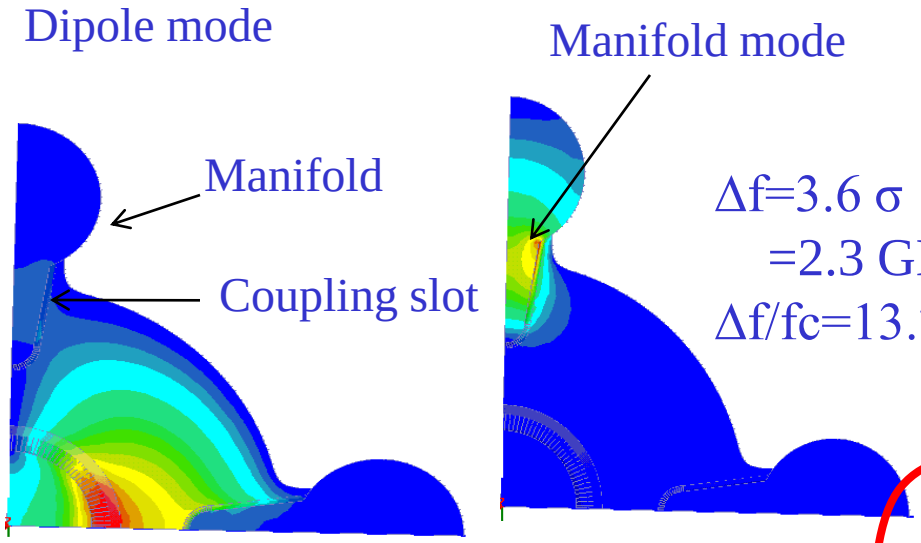


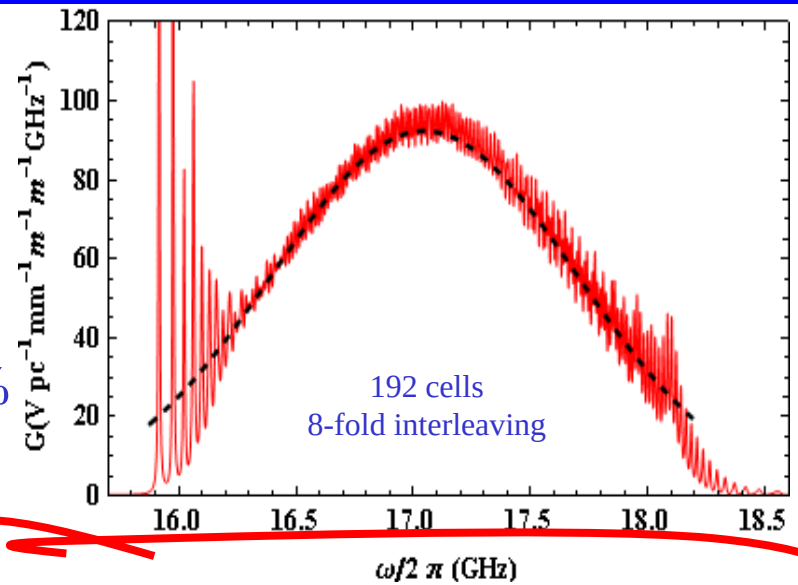


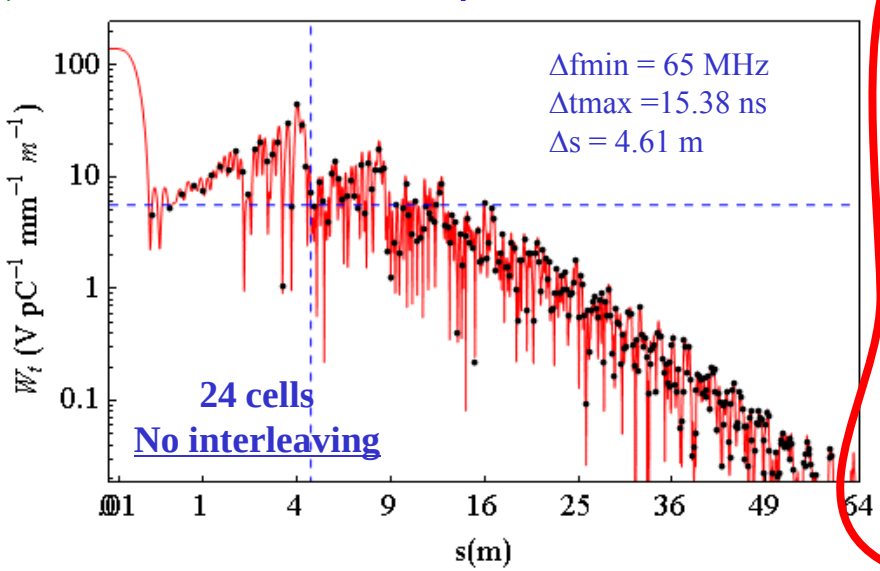
- Dispersion curves for select cells are displayed (red used in fits, black reflects accuracy of model)
- Provided the fits to the lower dipole are accurate, the wake function will be well-represented
- Spacing of avoided crossing (inset) provides an indication of the degree of coupling (damping Q)

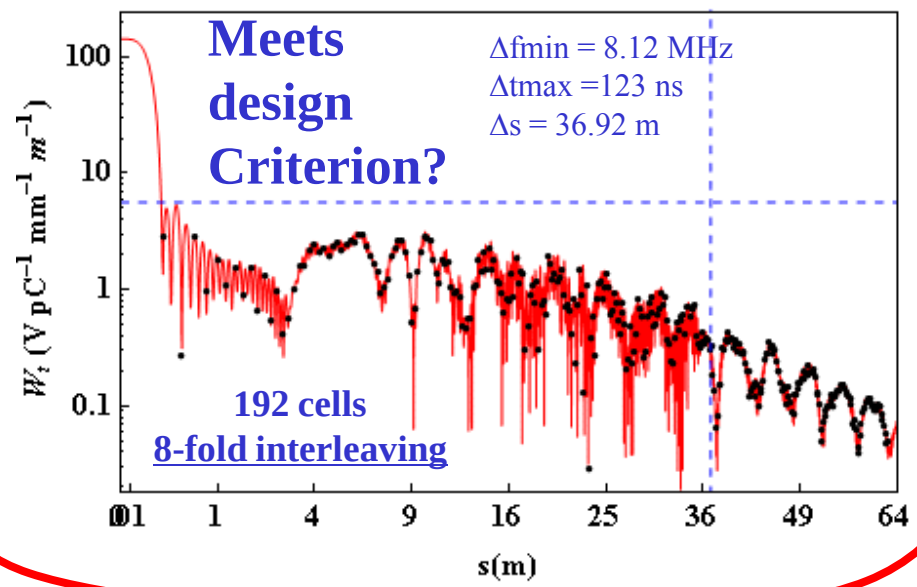


2.3 Summary of CLIC_DDS_C









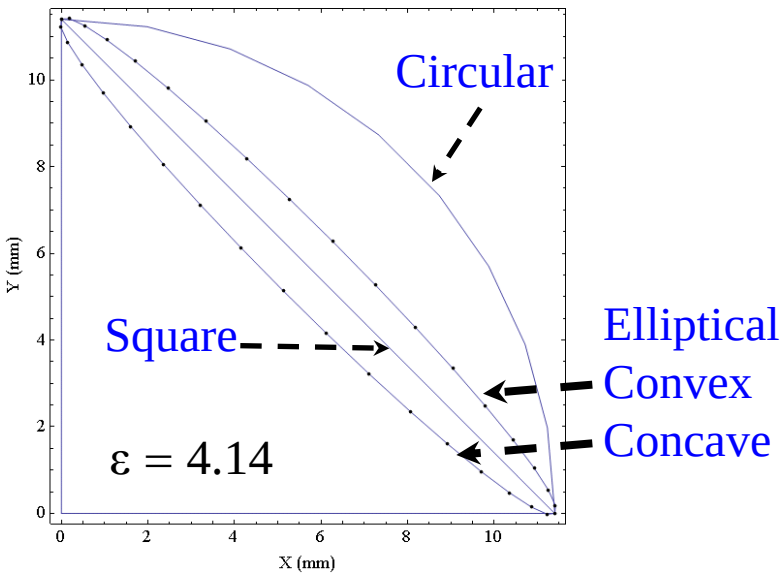
3. CLIC_DDS_E

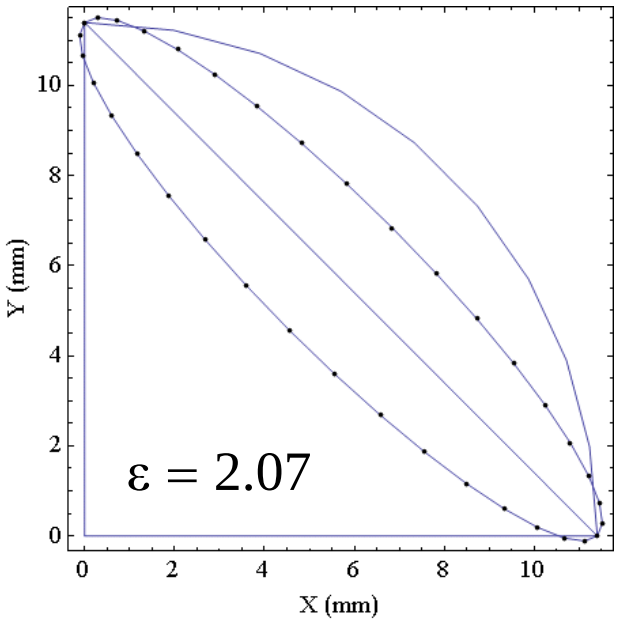
- Enhanced H-field on various cavity contours results in unacceptable ΔT (~65° K).

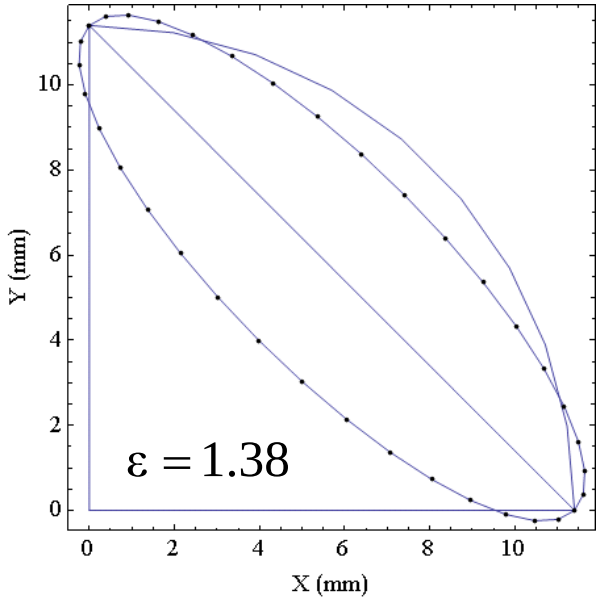
- Can the fields be redistributed such that a ~20% rise in the slot region is within acceptable bounds?
  ⇒Modify cavity wall

- Explore various ellipticities (R. Zennaro, A. D'Elia, V. Khan)

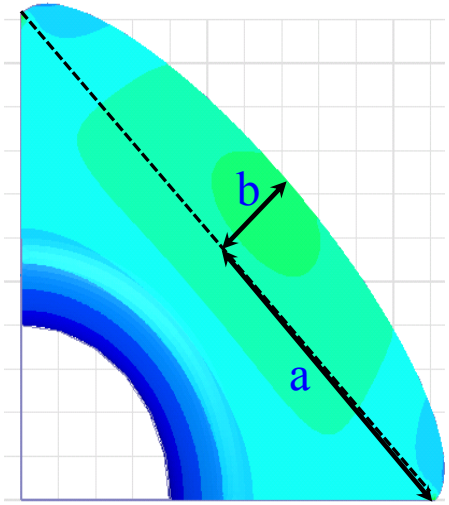
3. CLIC_DDS_E Elliptical Design





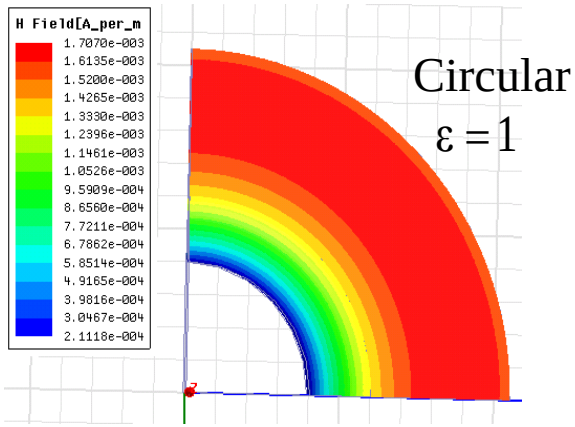


$$\varepsilon = \left(\sqrt{2} - 1\right)\frac{a}{b}$$

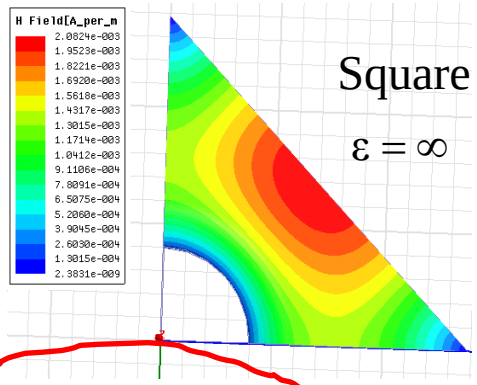


3. CLIC_DDS_E Elliptical Design –E Fields

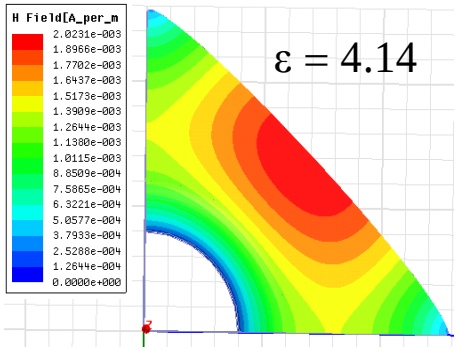
Single undamped cell
Iris radius=4.0 mm



Circular
$\varepsilon = 1$

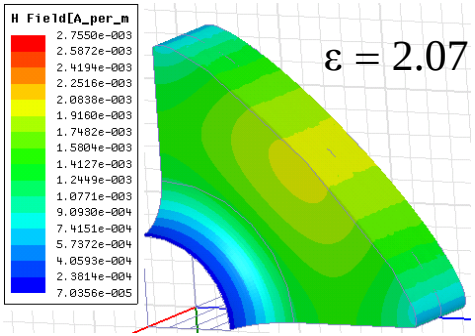


Square
$\varepsilon = \infty$

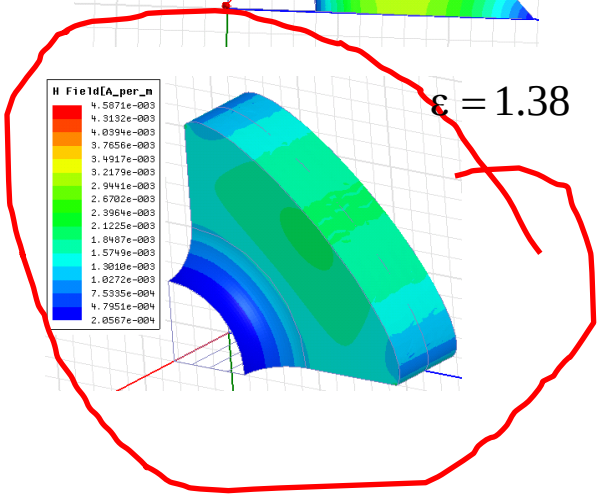


$\varepsilon = 4.14$

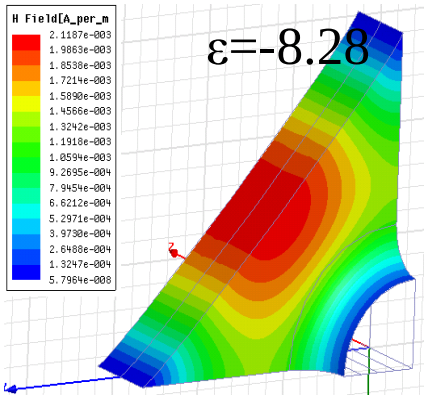
Convex ellipticity



$\varepsilon = 2.07$

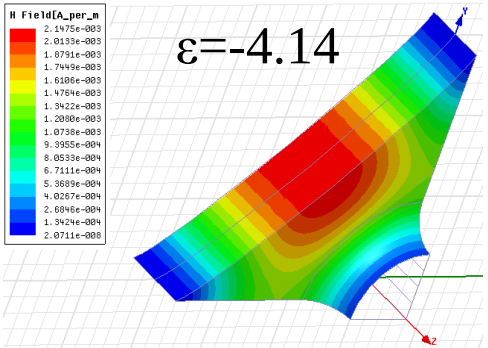


$\varepsilon = 1.38$

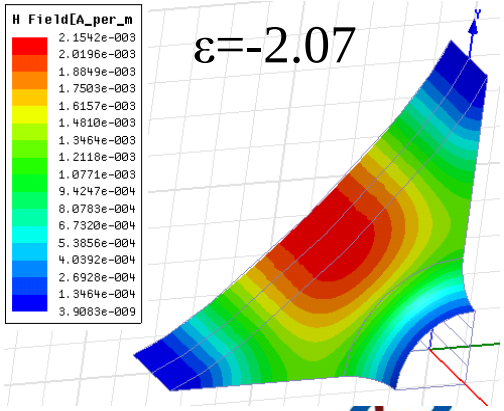


ε=-8.28

Concave ellipticity



ε=-4.14



ε=-2.07

3 CLIC_DDS_E Elliptical Design, Single Undamped Cell Dependence of Fields on ε

	Circular	Rectangular	Elliptical (Convex)					Elliptical (Concave)		
ε of cavity	1	∞	4.14	2.07	1.38	0.82	0.41	-8.28	-4.14	-2.07
f_{acc}(GHz)	12.24	12.09	11.98	12.0	11.99	11.98	11.98	11.9911	11.9919	11.9935
Eacc(V/m)	0.43	0.43	0.42	0.43	0.43	0.42	0.42	0.43	0.43	0.42
H^{sur}_{max} /Eacc (mA/V)	3.64	4.86	4.71	4.54	4.29	3.75	3	4.94	4.99	5.11
E^{sur}_{max} /E_{acc}	2.27	2.27	2.33	2.28	2.28	2.33	2.33	2.27	2.27	2.33

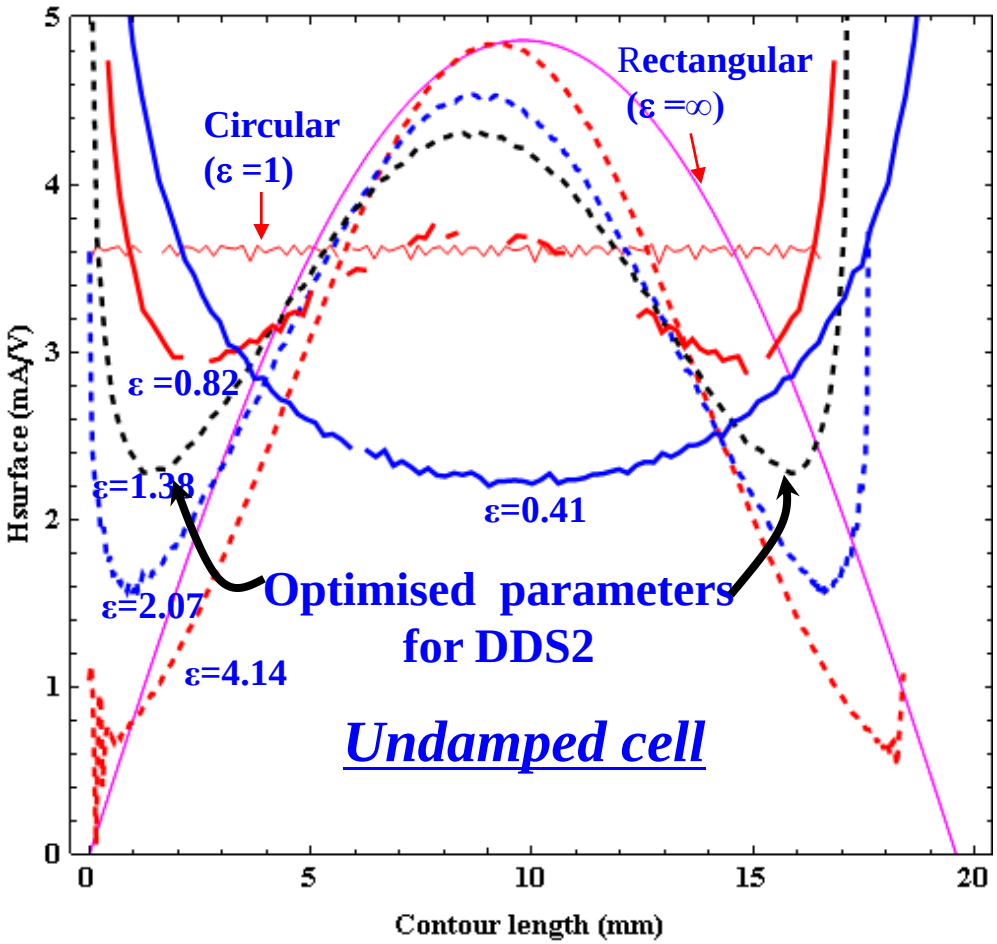
Iris radius = 4. 0 mm
Iris thickness = 4.0 mm

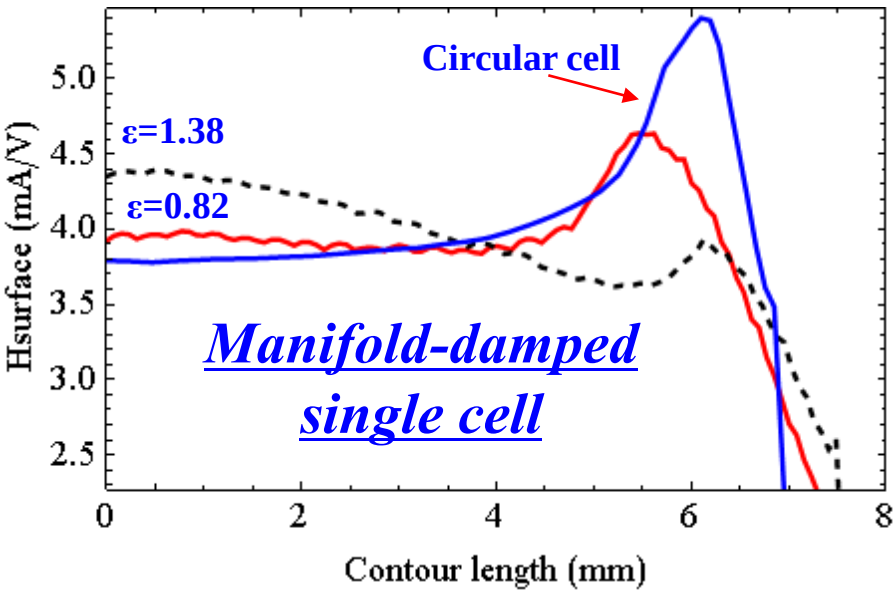
Chosen design

3. CLIC_DDS_E Single-Cell Surface Field Dependence on ε

Optimisation of cavity shape for min H_s^{max}

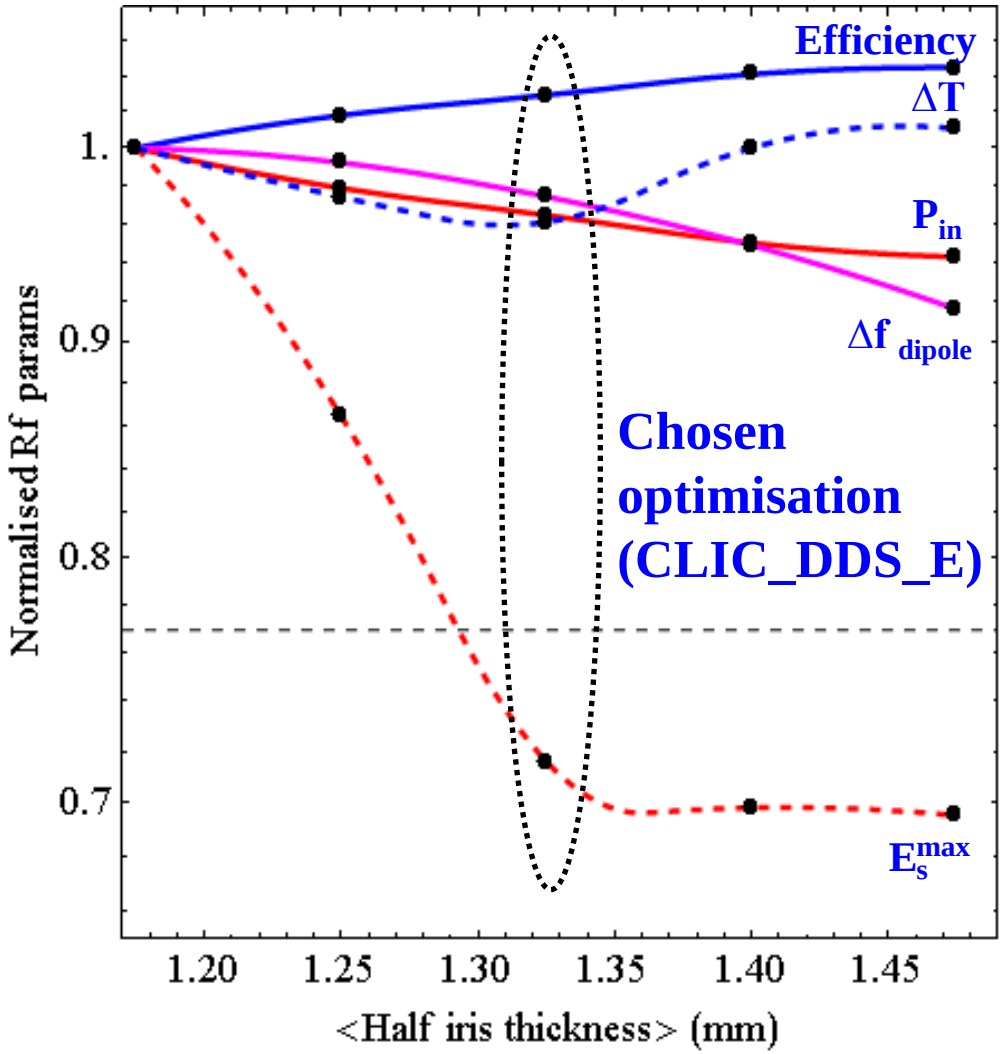
- Iris radius ~4mm. For both geometries
- Averaging surface H over contour ⇒ε =1.38



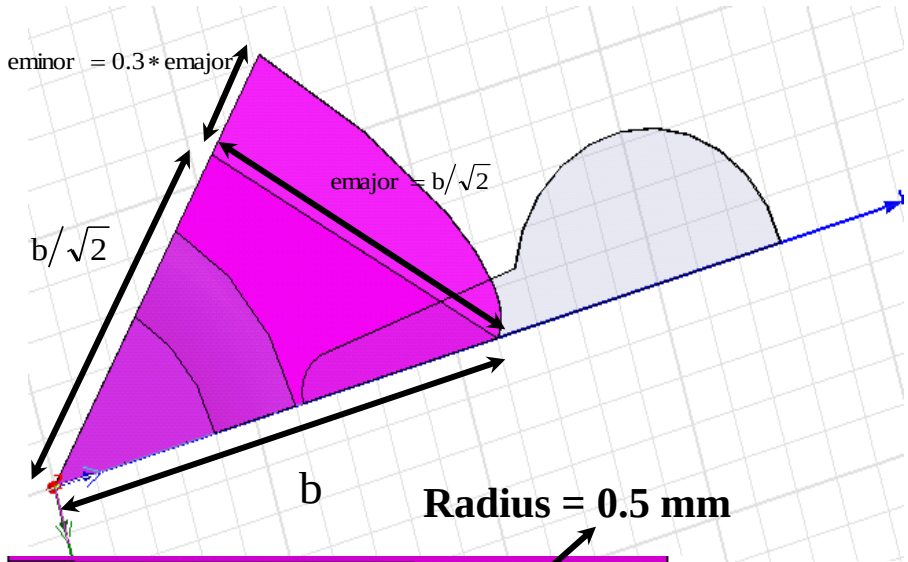


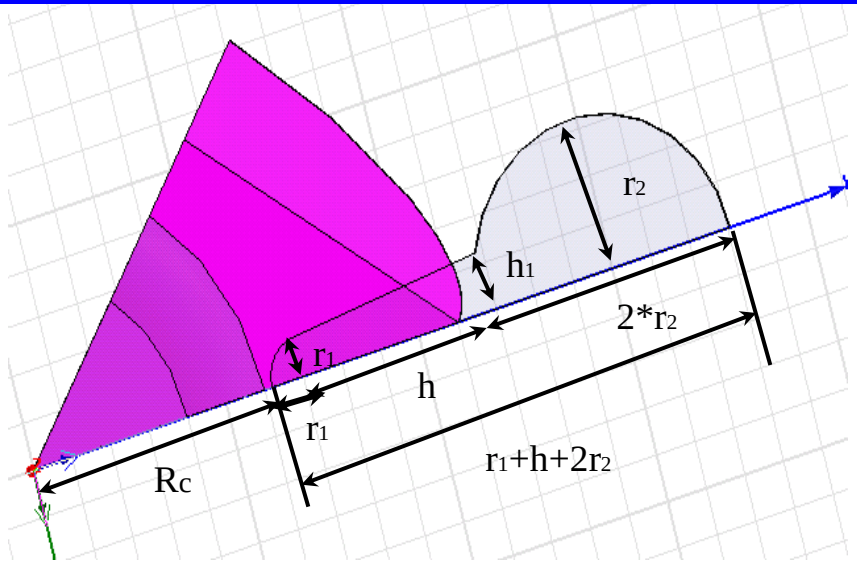
3. CLIC_DDS_E, Optimisation of: E_s^{max} , Δf and Efficiency

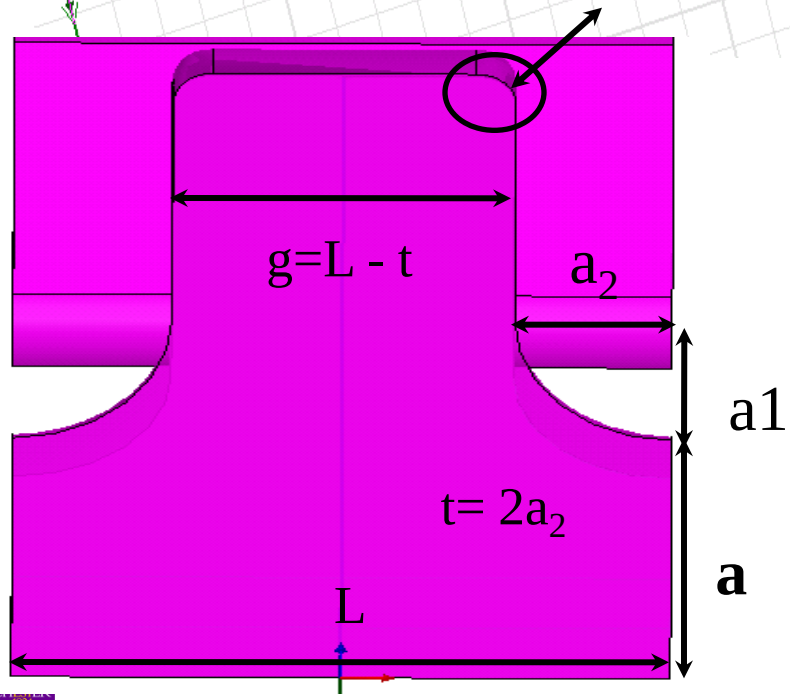
- Optimisation of parameters based on manifold damped structures.
- Vary half-iris thickness.
- 3-cell simulations, with intermediate parameters obtained via interpolation.
- Choose parameters with minimal surface E-field, pulse temperature rise, and adequate efficiency.



3. CLIC_DDS_E: Detailed Geometry



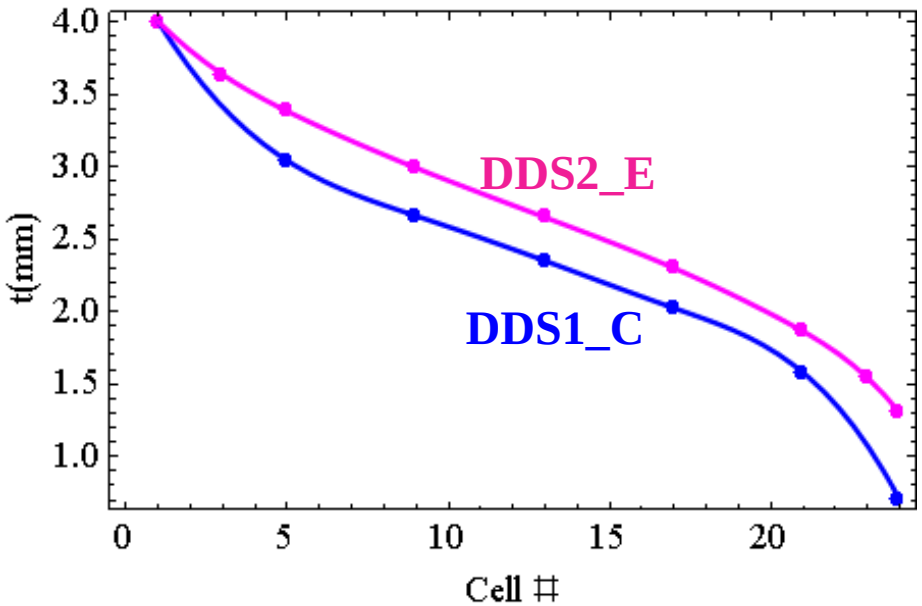


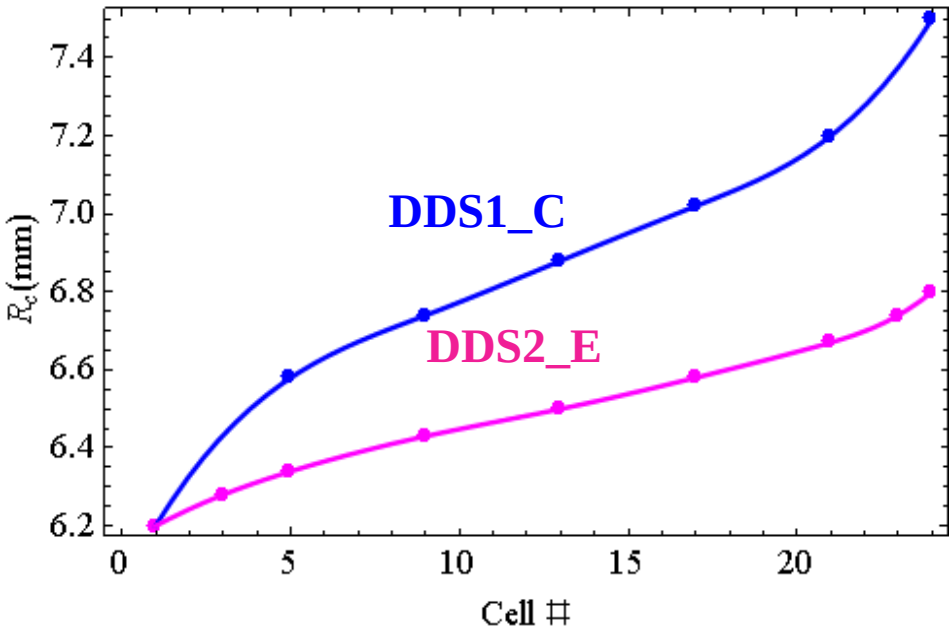


Constant parameters (mm)	All cells
L	8.3316
r1	0.85
h	4.5
h1	1.25
Fillet @ cavity and manifold joint	1.0
Rounding of cavity edge	0.5

Variable parameters (mm)	Cell #1	Cell#24
a	4.0	2.3
b	11.01	10.039
a2	2.0	0.65
a1	a2	2a2
Rc	6.2	6.8
r2	3.25	2.3

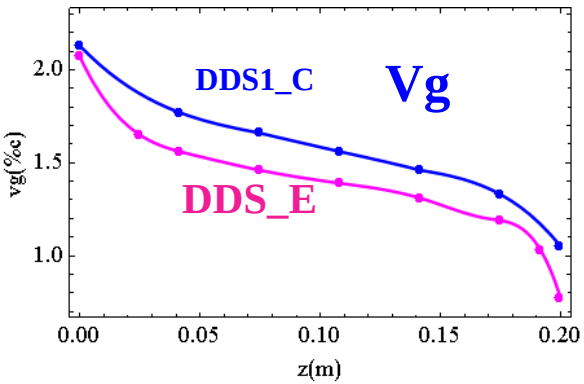
3. Impact on Parameters: CLIC_DDS_C to CLIC_DDS_E

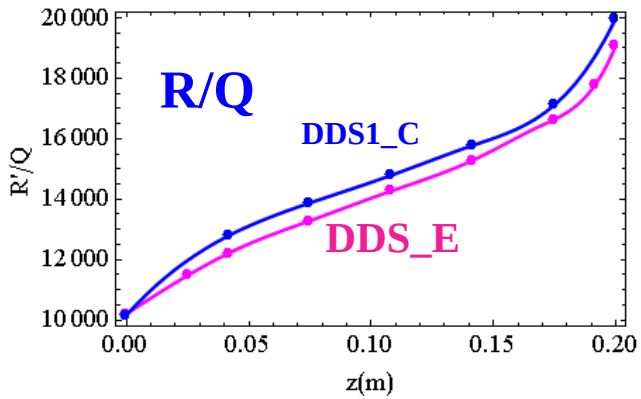


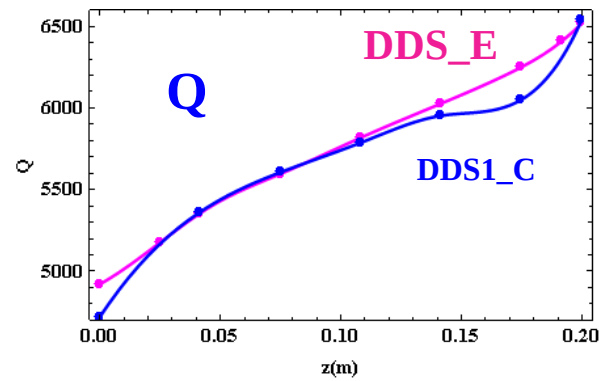


Parameter	DDS1_C	DDS2_E	Modified to achieve
Shape	Circular	Elliptical	Min. H-field
<Iris thickness> (mm)	2.35	2.65	Min. E-field
R_c 1to 24 (mm)	6.2-7.5	6.2-6.8	Critical coupling

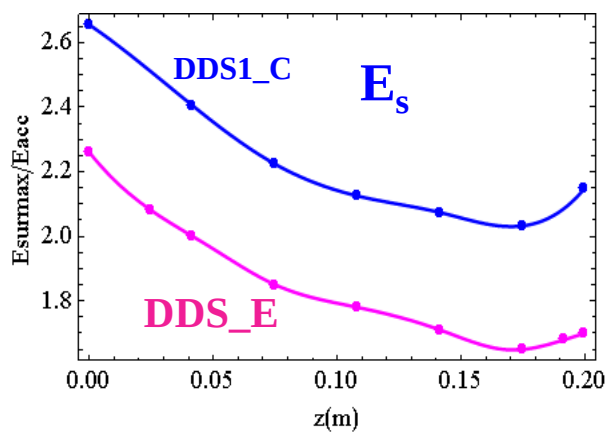
3. CLIC_DDS_E
-Fundamental Mode Parameters

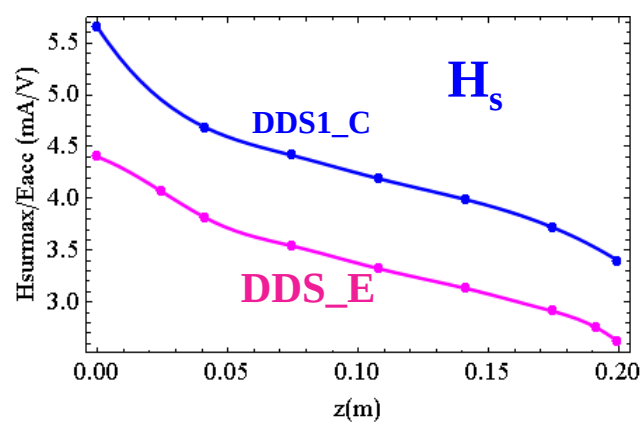




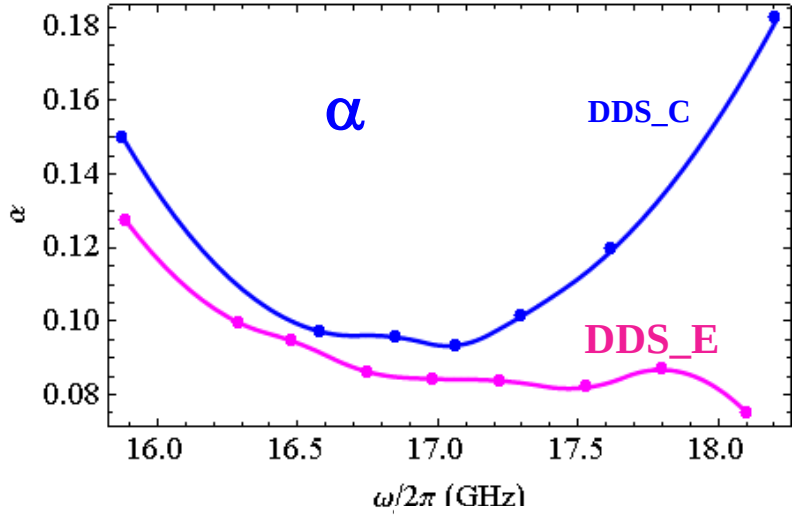


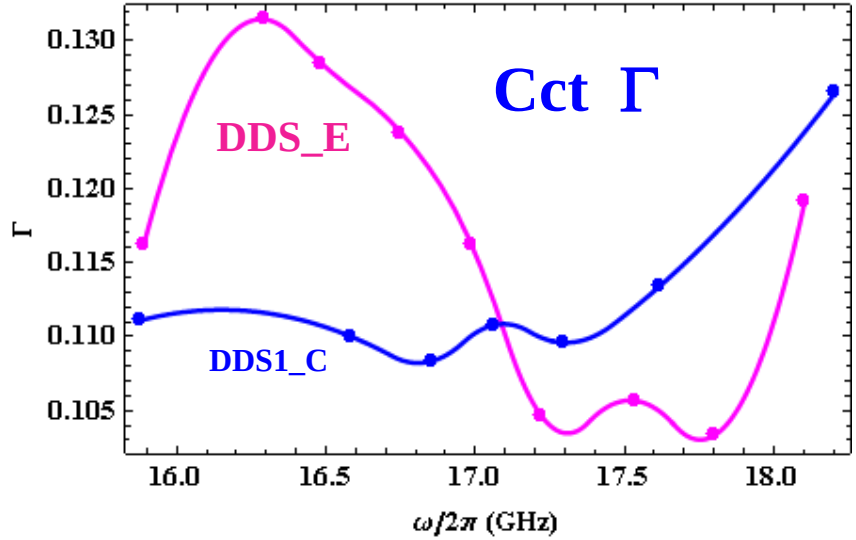
- Group velocity is reduced due increased iris thickness
- R/Q reduced slightly
- Surface field and ΔT reduced significantly by using elliptical cells



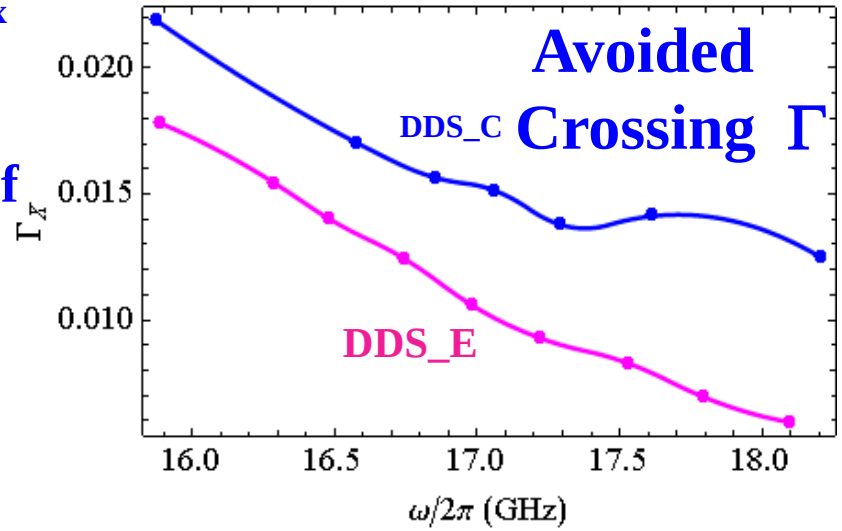


3. Wake Function for CLIC_DDS_E -Dipole Circuit Parameters





- Avoided crossing Γ_x is significantly reduced due to the smaller penetration of the manifold.
- Some re-optimisation could improve this

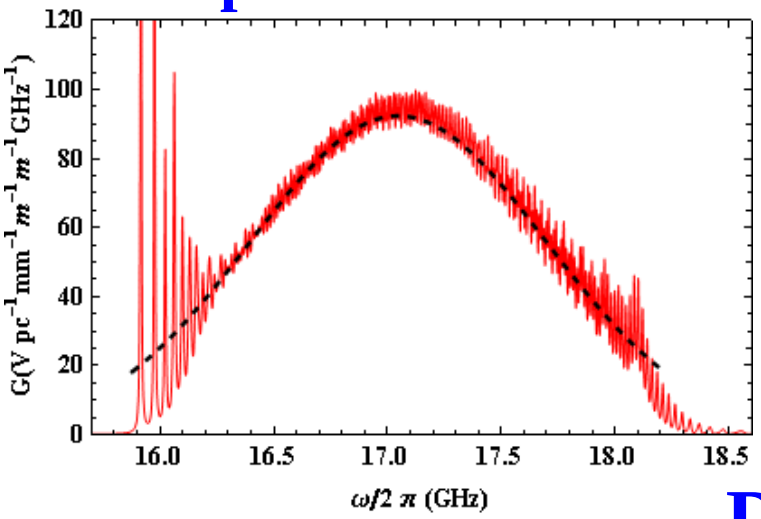


$\Delta f = 3.5\ \sigma$
$= 2.2$ GHz
$\Delta f / f_c = 13.75\%$

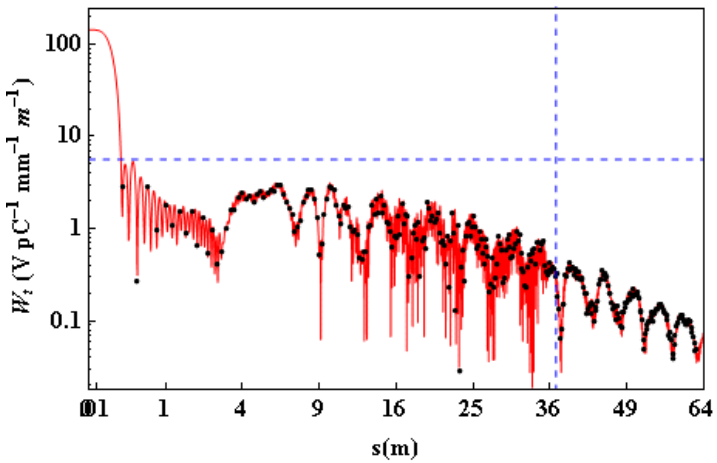
$a_1 = 4$mm
$a_{24} = 2.3$mm

3. Consequences on Wake Function

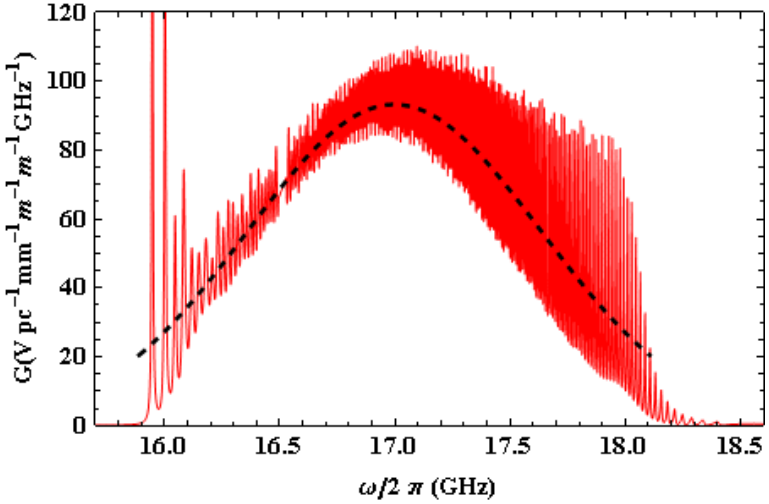
Spectral Function

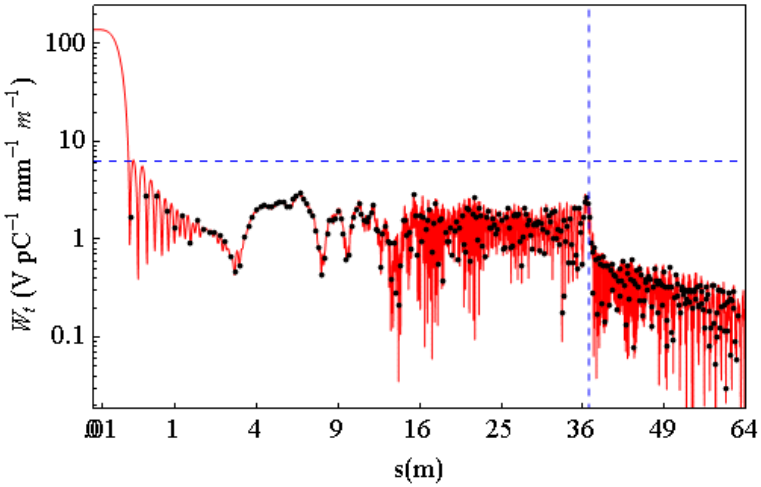


Wake Function



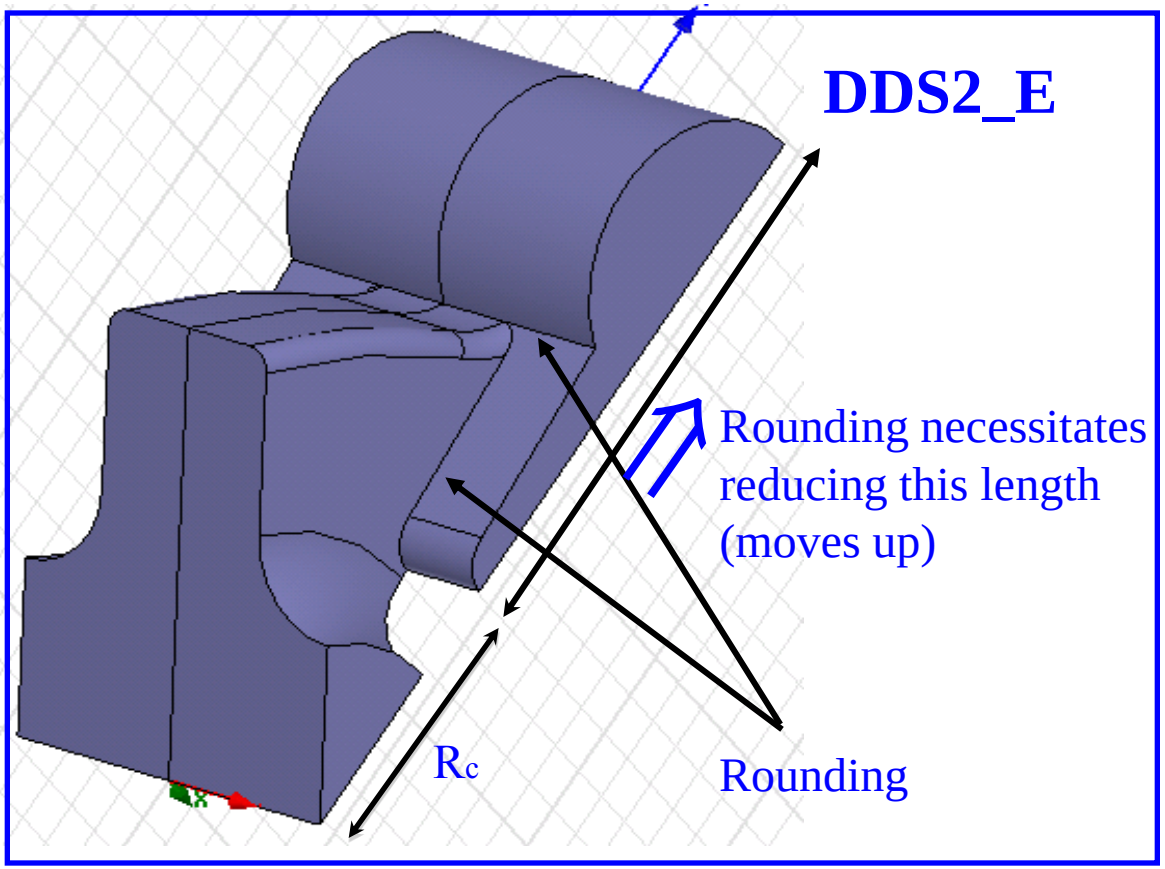
DDS1_C

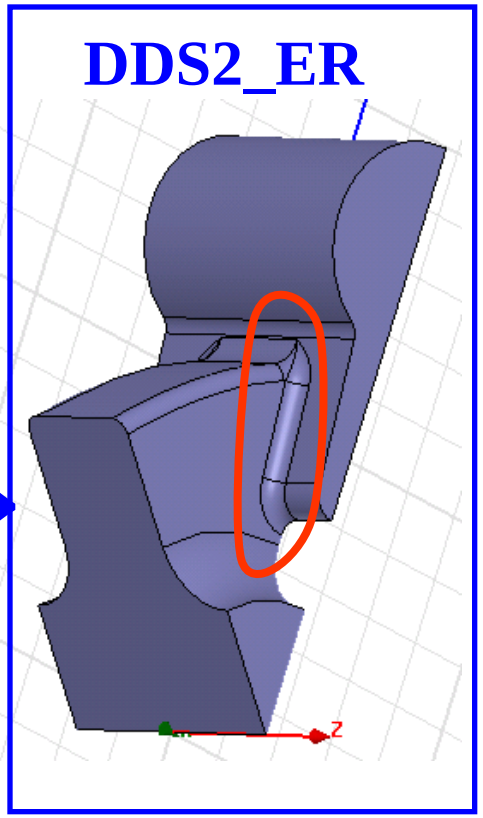




DDS2_E

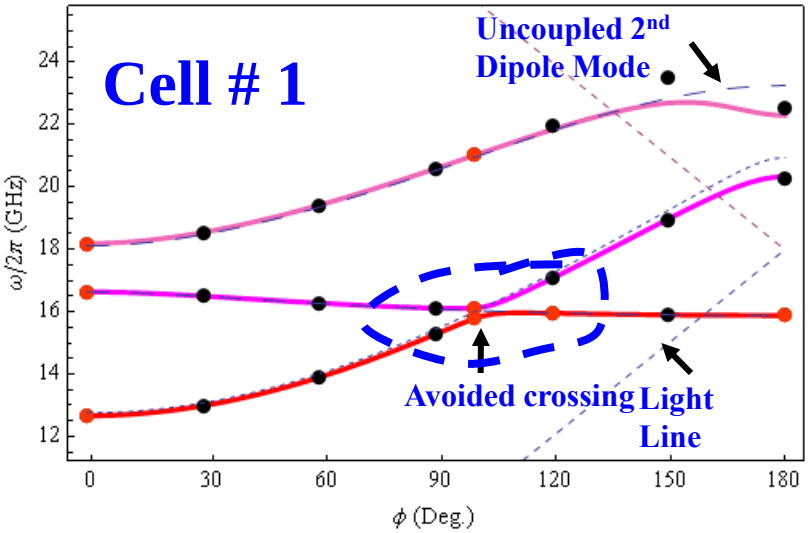
4. CLIC_DDS_E: Modified Design Based on Engineering Considerations

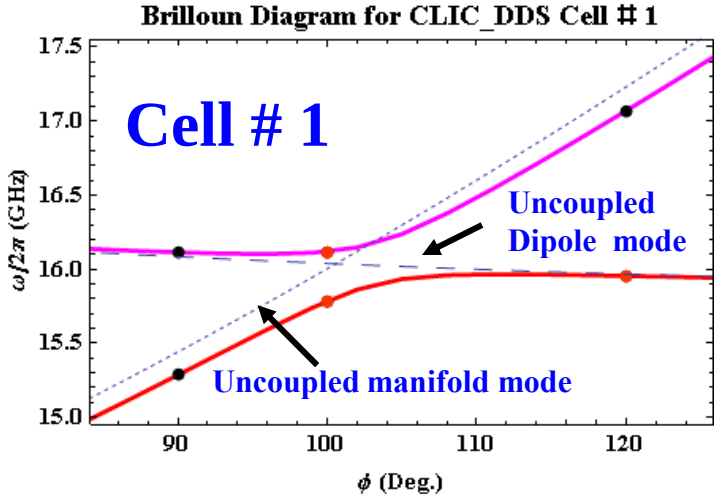


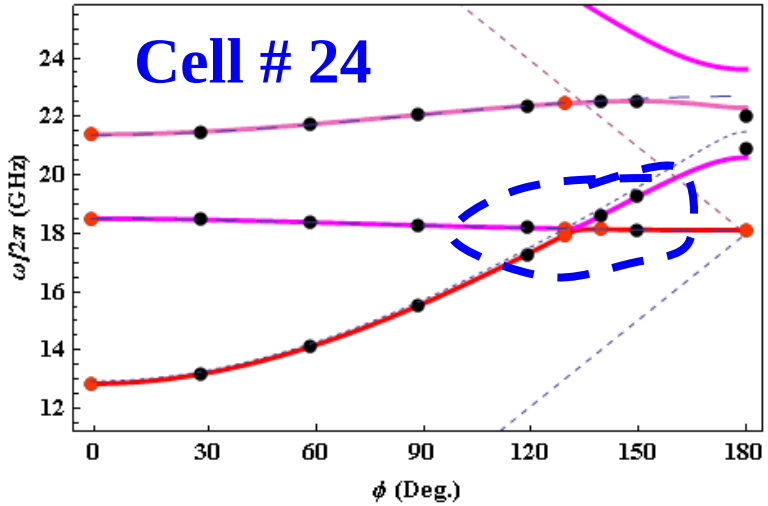


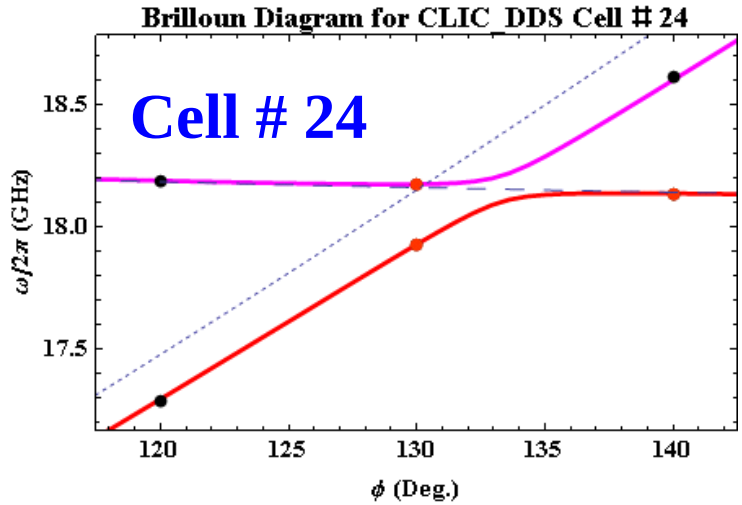
- To facilitate machining of indicated sections, roundings are introduced (A. Grudiev, A. D'Elia).
- In order to accommodate this, R_c needs to be increased ⇒ DDS2_ER.
- Coupling of dipole modes is reduced and wake-suppression is degraded. How much?

4. CLIC_DDS_ER Dispersion Curves



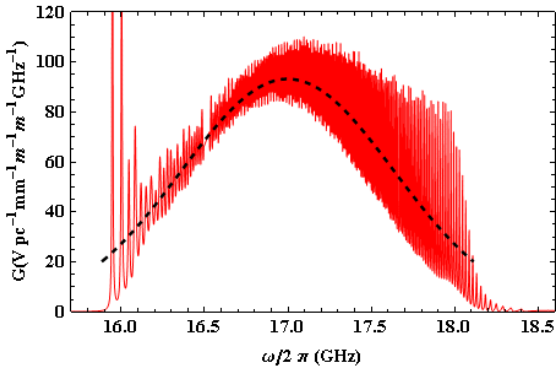


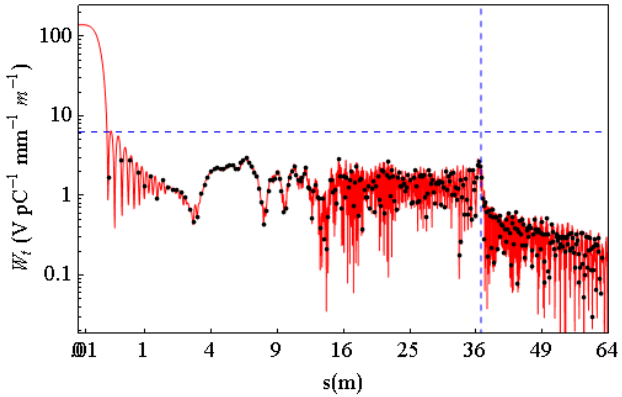




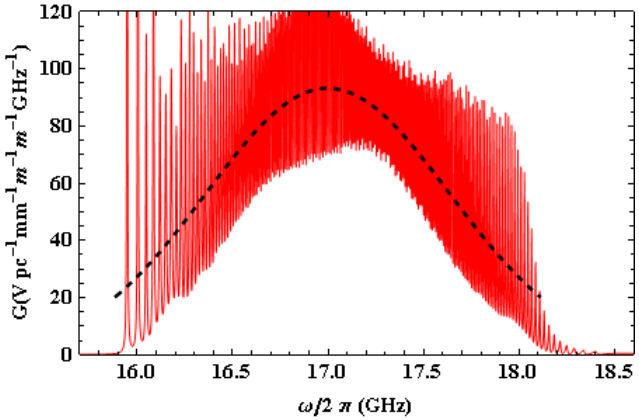
4. CLIC_DDS_E vs CLIC_DDS_ER Wakefield

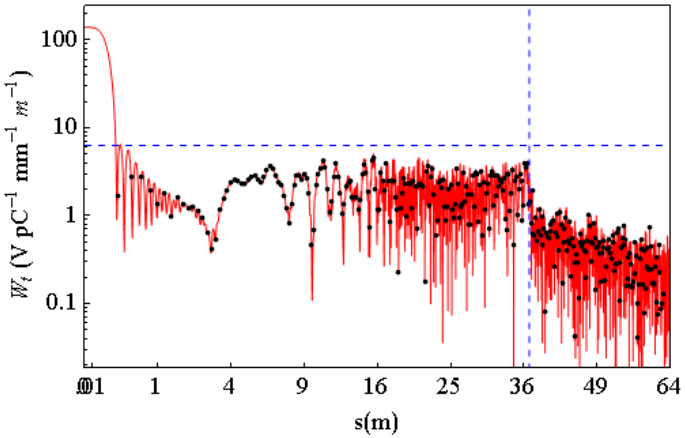
Spectral Function **Wakefunction**





CLIC_DDS_E :Rc=6.2 - 6.8 mm (optimised penetration)

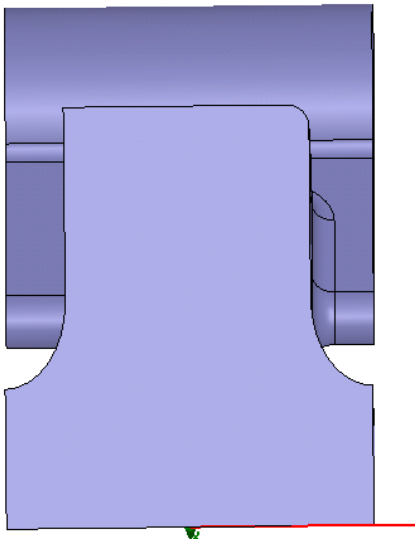


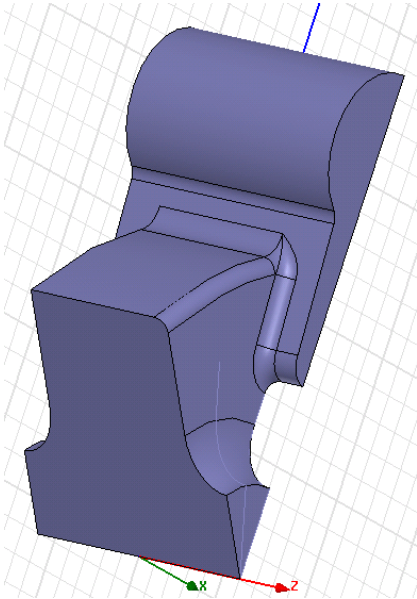


- **CLIC_DDS_ER : Rc=6.8 mm const (a single one of these structures constitutes CLIC_DDS_A, being built for HP testing)**
- **Wakefield suppression is degraded but still within acceptable limits.**

4. CLIC_DDS_A: Structure Suitable for High Power Testing

- Info. on the ability of the 8-fold interleaved structure to sustain high e.m. fields and sufficient ΔT can be assessed with a single structure.
- Single structure fabricated in 2010/1st quarter 2011, CLIC_DDS_A, to fit into the schedule of breakdown tests at CERN.





- Design is based on CLIC_DDS_ER
- To facilitate a rapid design, the HOM couplers have been dispensed with in this prototype.
- Mode launcher design utilised
- SRF design complete!
- Mechanical drawings, full engineering design completed!
- Qualification end cells fabricated. Recently received (Oct 15 2010!)!

4. CLIC_DDS_A: Structure Suitable for High Power Testing

- Non-interleaved 24 cell structure –first structure of 8-fold interleaved structure chosen.
- High power (~71MW I/P) and high gradient testing
- To simplify mechanical fabrication, uniform manifold penetration chosen

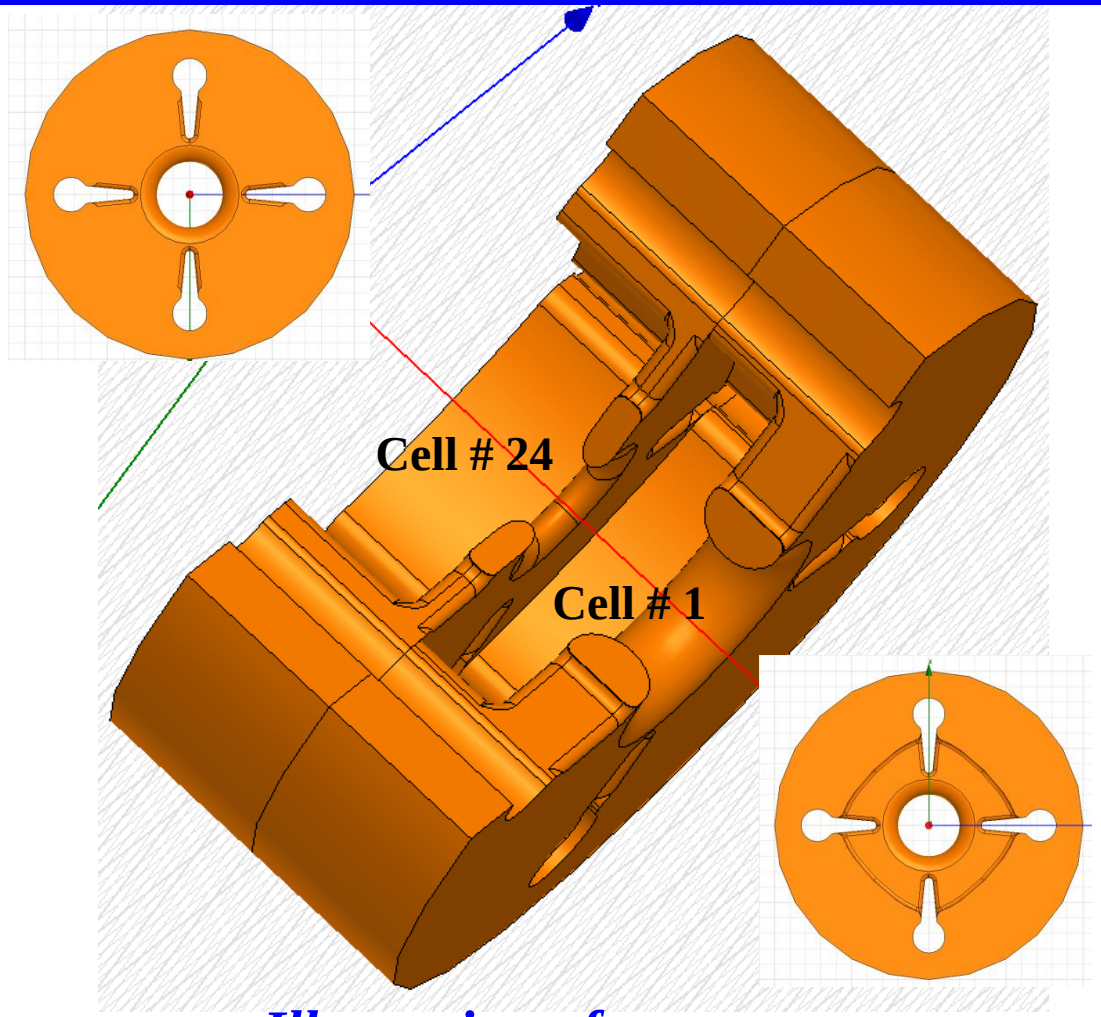
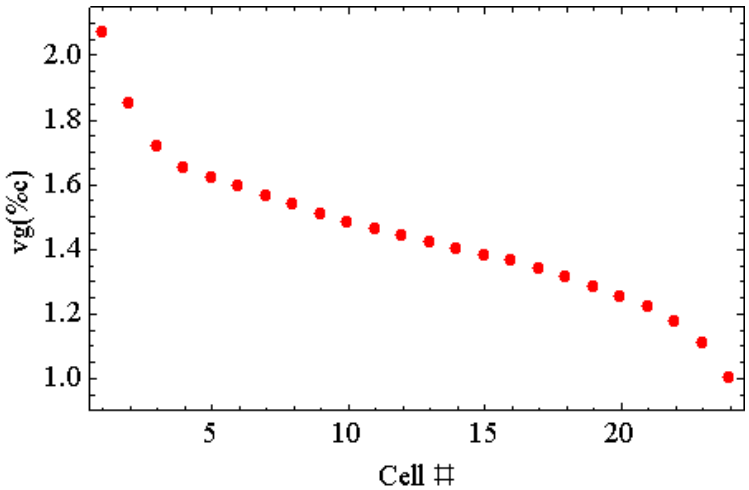
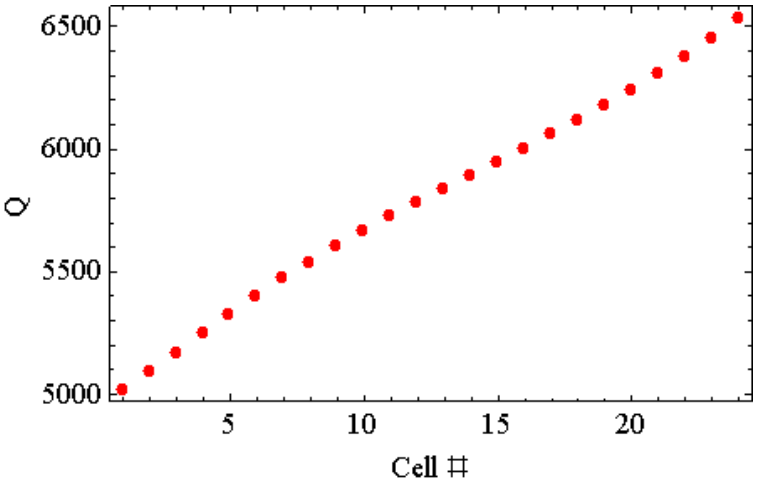
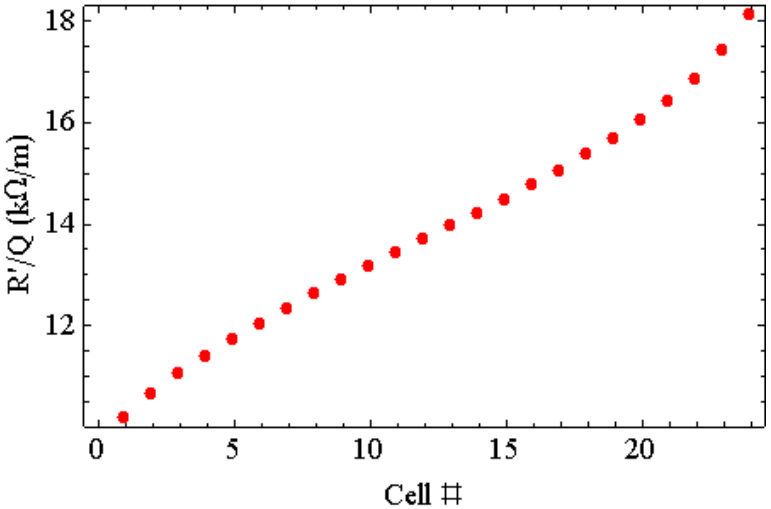


Illustration of extrema of a 24 cell structure

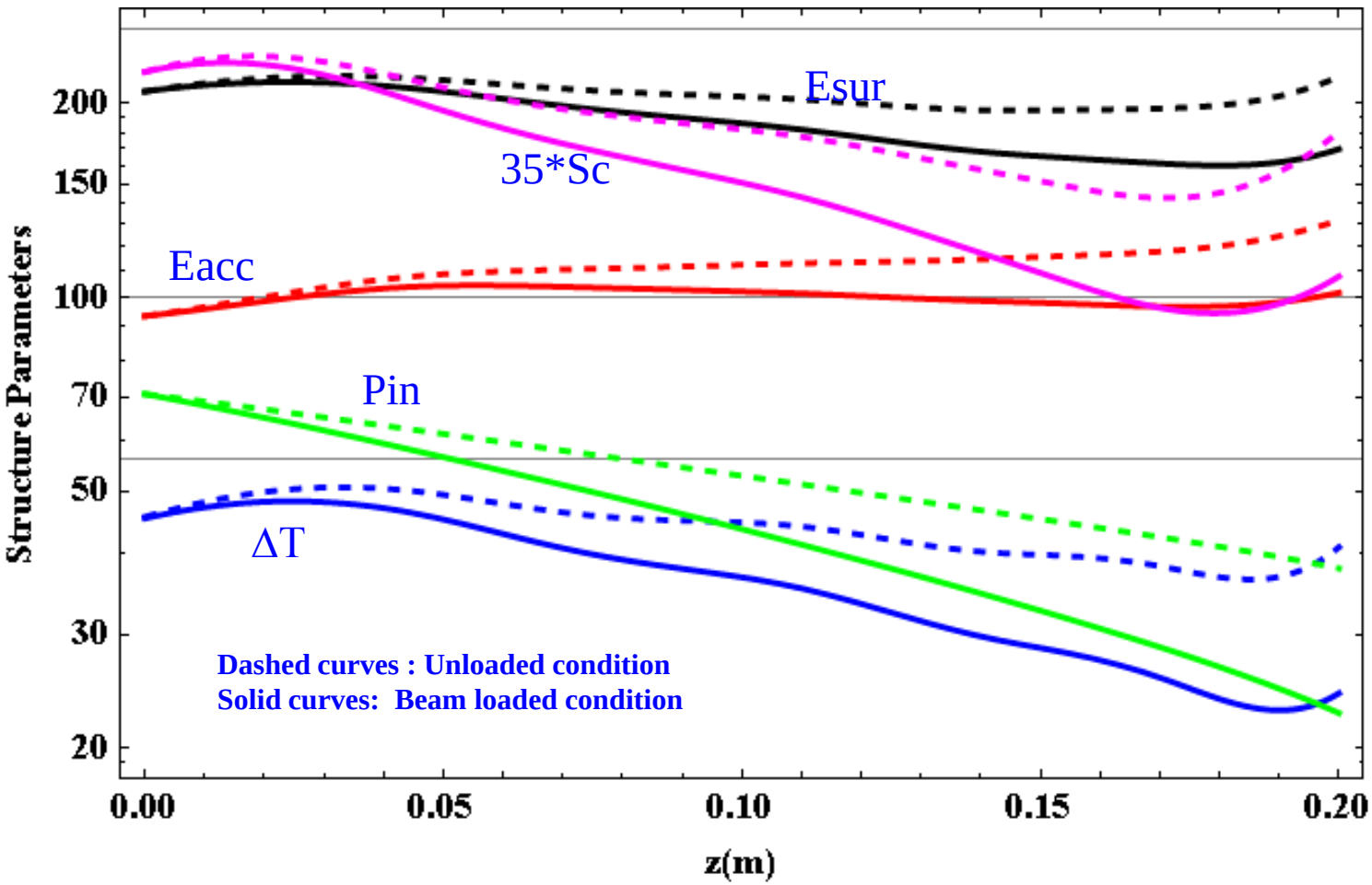
4. CLIC_DDS_A Fundamental Mode Parameters







4. CLIC_DDS_A Parameters



Max. Values

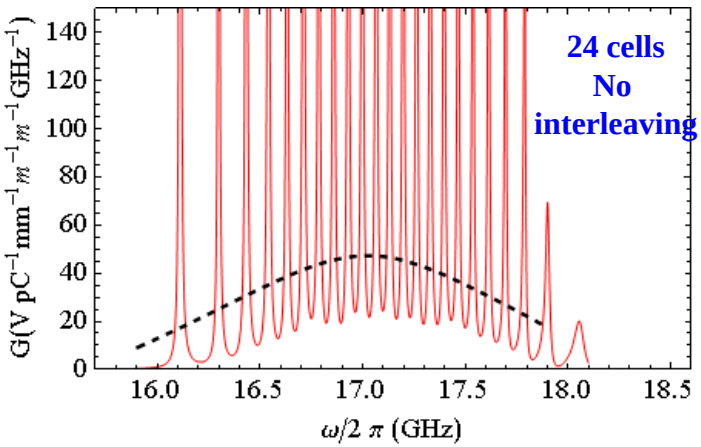
Esur=220 MV/m
ΔT = 51 K
Pin= 70.8
Eacc_UL=131 MV/m
Sc=6.75 W/μm^2
RF-beam-eff=23.5%

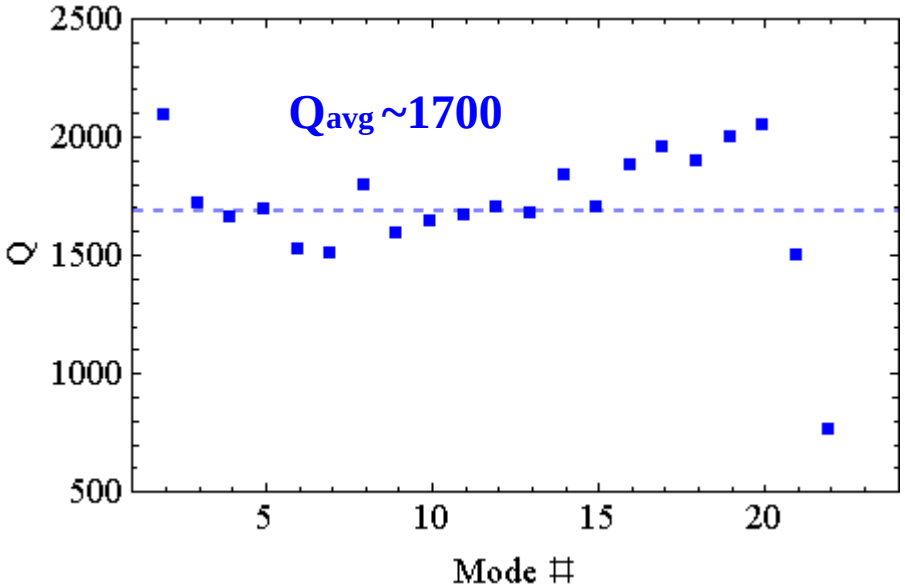
CLIC_G Values

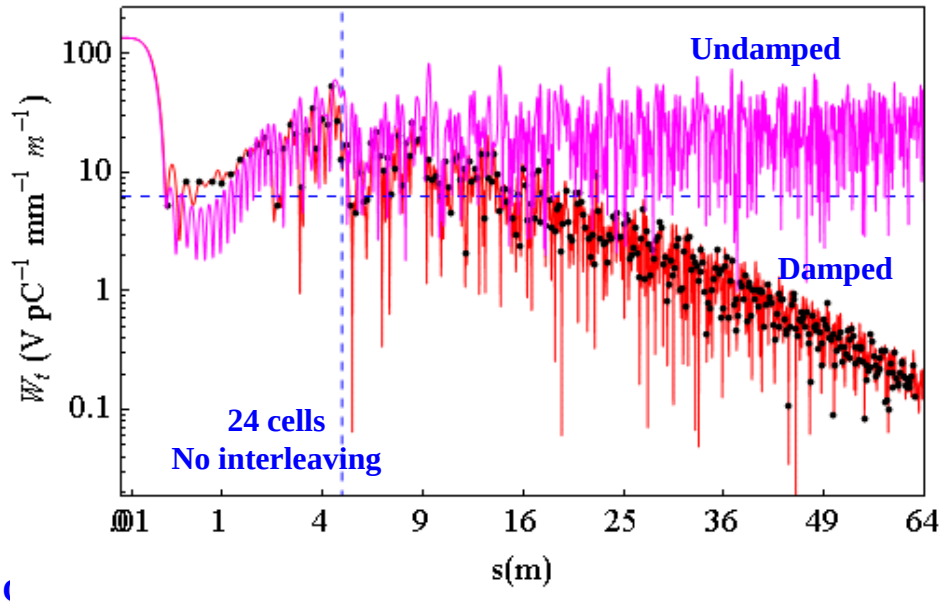
Esur=240 MV/m
ΔT = 51 deg.
Pin= 63.8
Eacc_UL=128 MV/m
Sc=5.4 W/μm^2
RF-beam-eff=27.7%

4. CLIC_DDS_A Wake

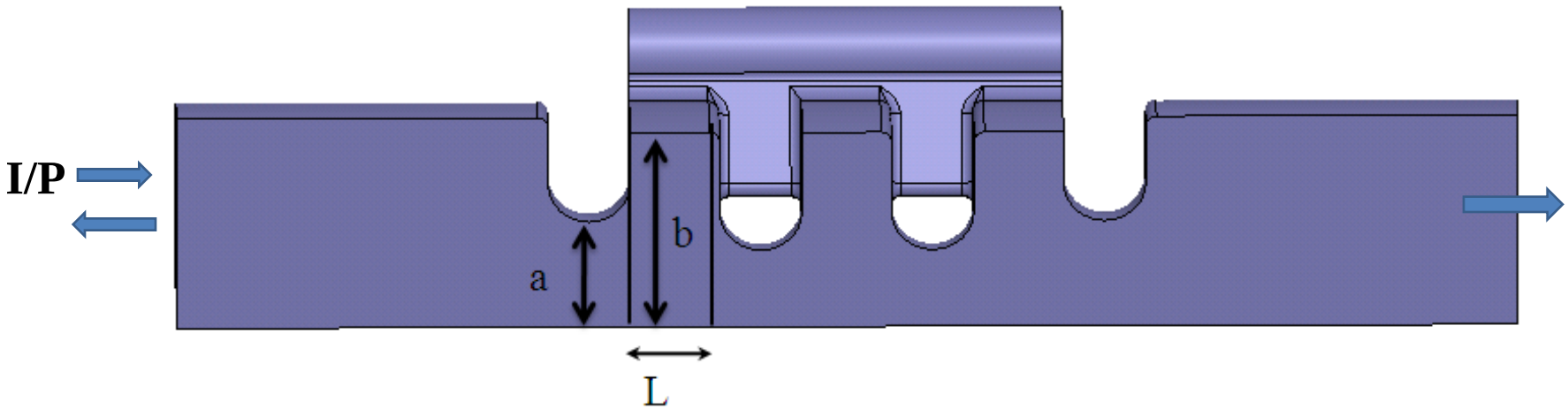
- Wake of a non-interleaved 24 cell structure –first structure of 8-fold interleaved structure chosen.
- Motivated by high gradient testing
- Wake is measurable and provides a useful comparison to simulations (but will not, of course, meet beam dynamics criteria)







4. Matching CLIC_DDS_A



- **Firstly, match-out either end of structure with regular cells:**
  - **Structure for test will utilise a mode launcher**
  - **Initially, simulate a structure with one regular cell and two matching cells at either end and we study the minima in S_{11} as a function of the geometrical parameters of the matching cells (a, L –adopt L variation, rather than b, from space considerations)**
  - **Add additional (2, then 3) identical standard cells (const. imp) and follow the same procedure and modify parameters of matching cells to minimise S_{11}**
  - **The matching condition (on a, L) is that which coincident with all 3 simulations.**
- **Secondly, once complete, match-out the full, tapered structure based on this match.**

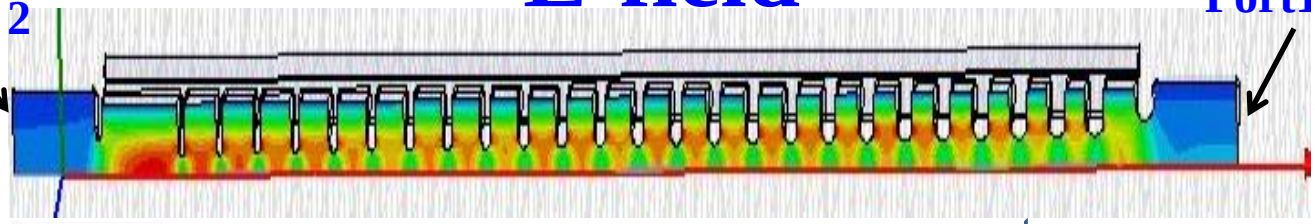
4. CLIC_DDS_A

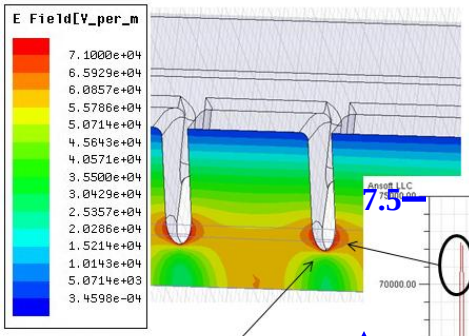
- Match-out the full, tapered structure
- E-field and S_{11} shown

E-field

Port 2

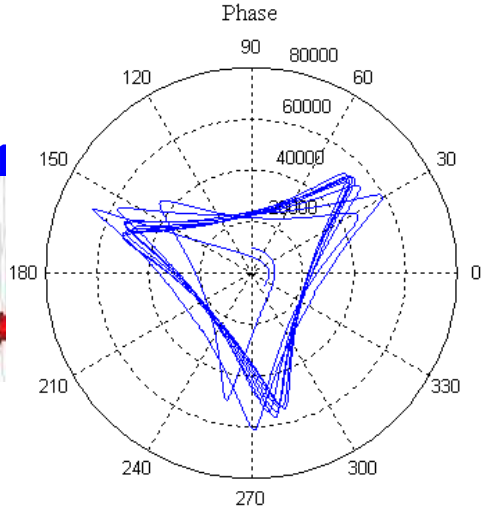
Port1



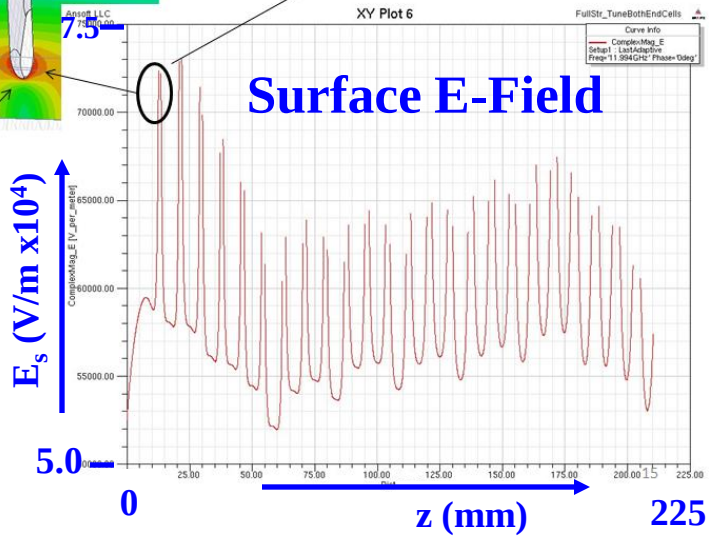


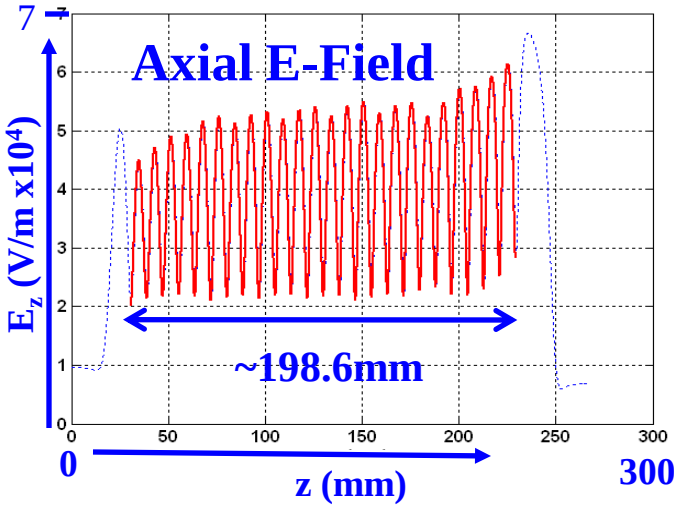
Matching cell

Beam



Matching side=72.34MV/m
Regular cell side= 72.175MV/m
Ratio=0.2%

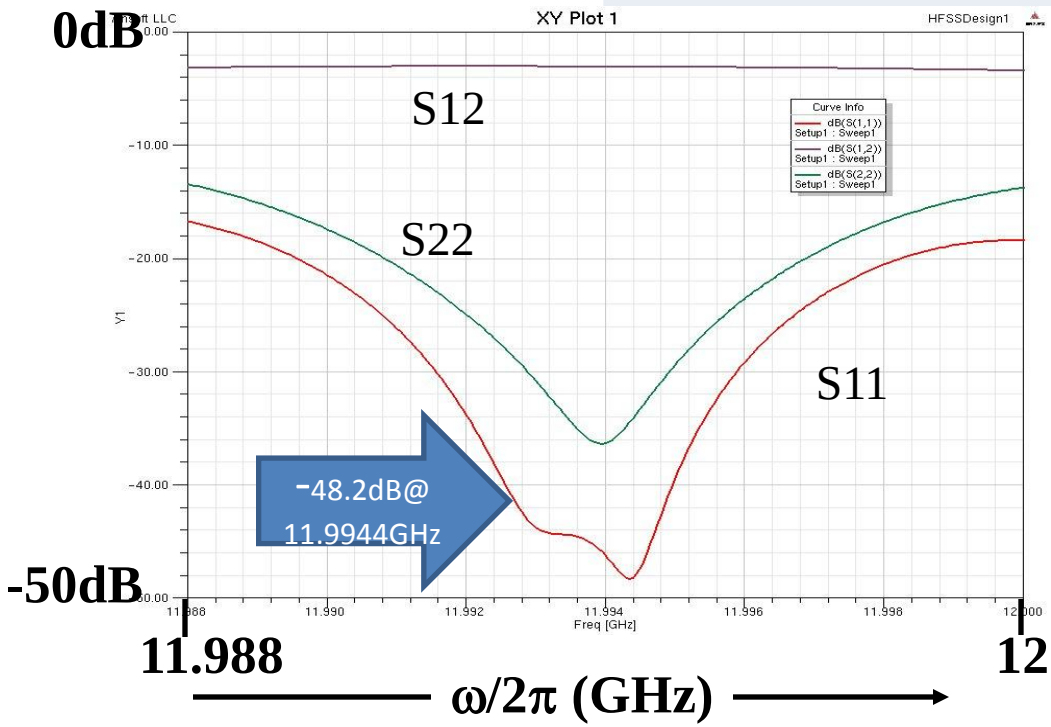


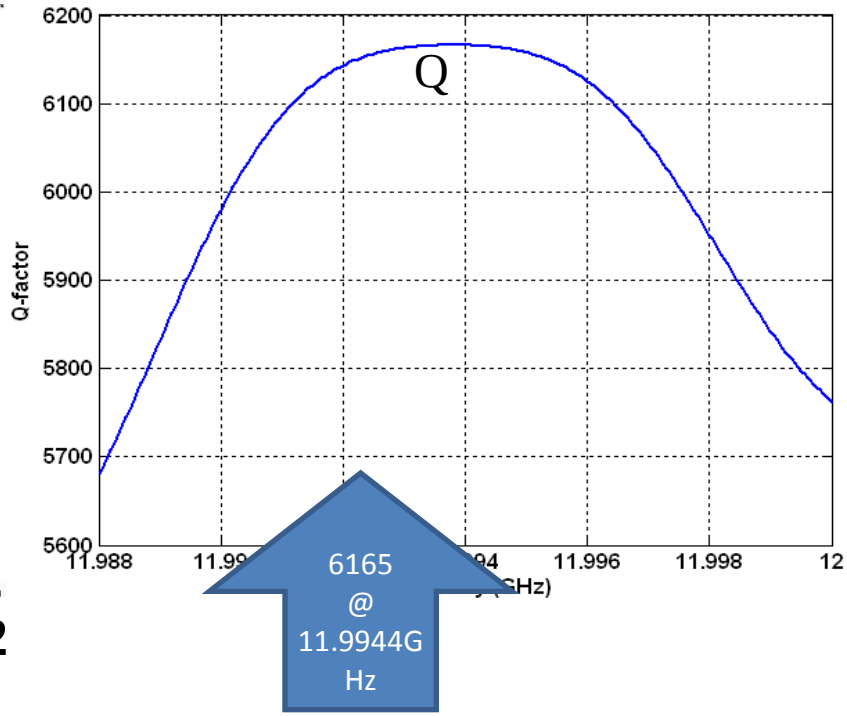


A. D'Elia

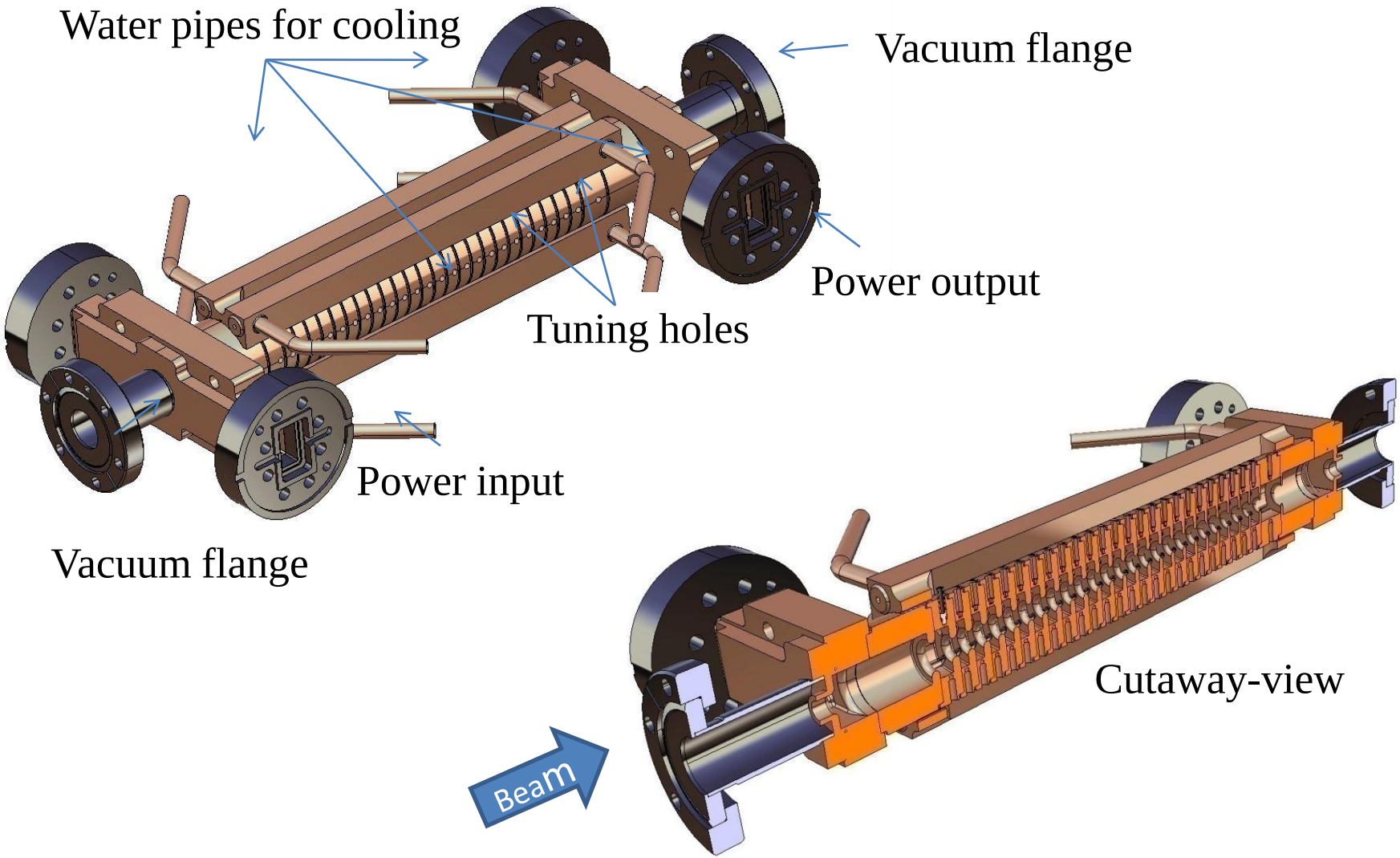
4. CLIC_DDS_A S Params

V_{26} [V]@P_{in} = 1 W	2678
G_{26} [V/m]@P_{in} = 1 W	13481
P_{in} [MW]@<G_{26}=100MV/m>	55.03



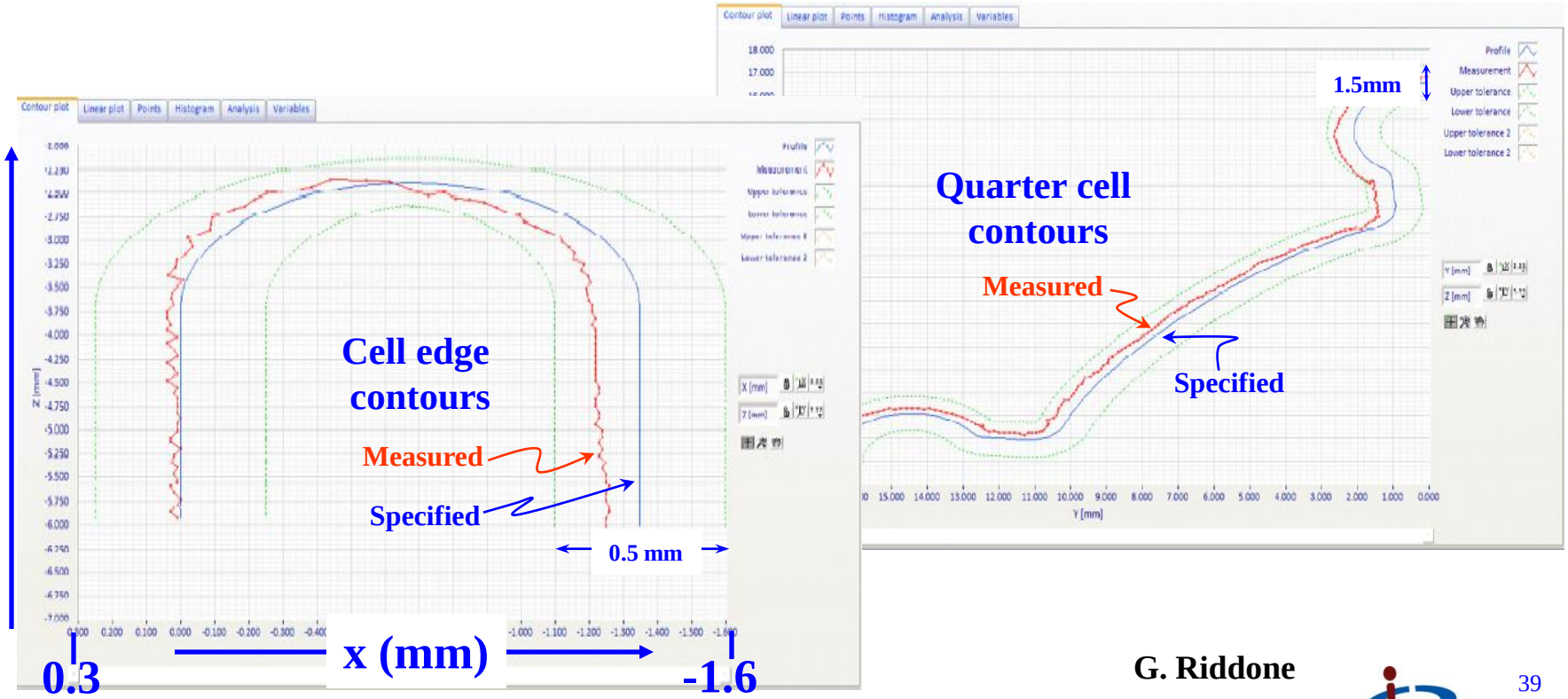


4. Mechanical Eng. Design of DDS_A



4. Cell Qualification of CLIC_DDS_A

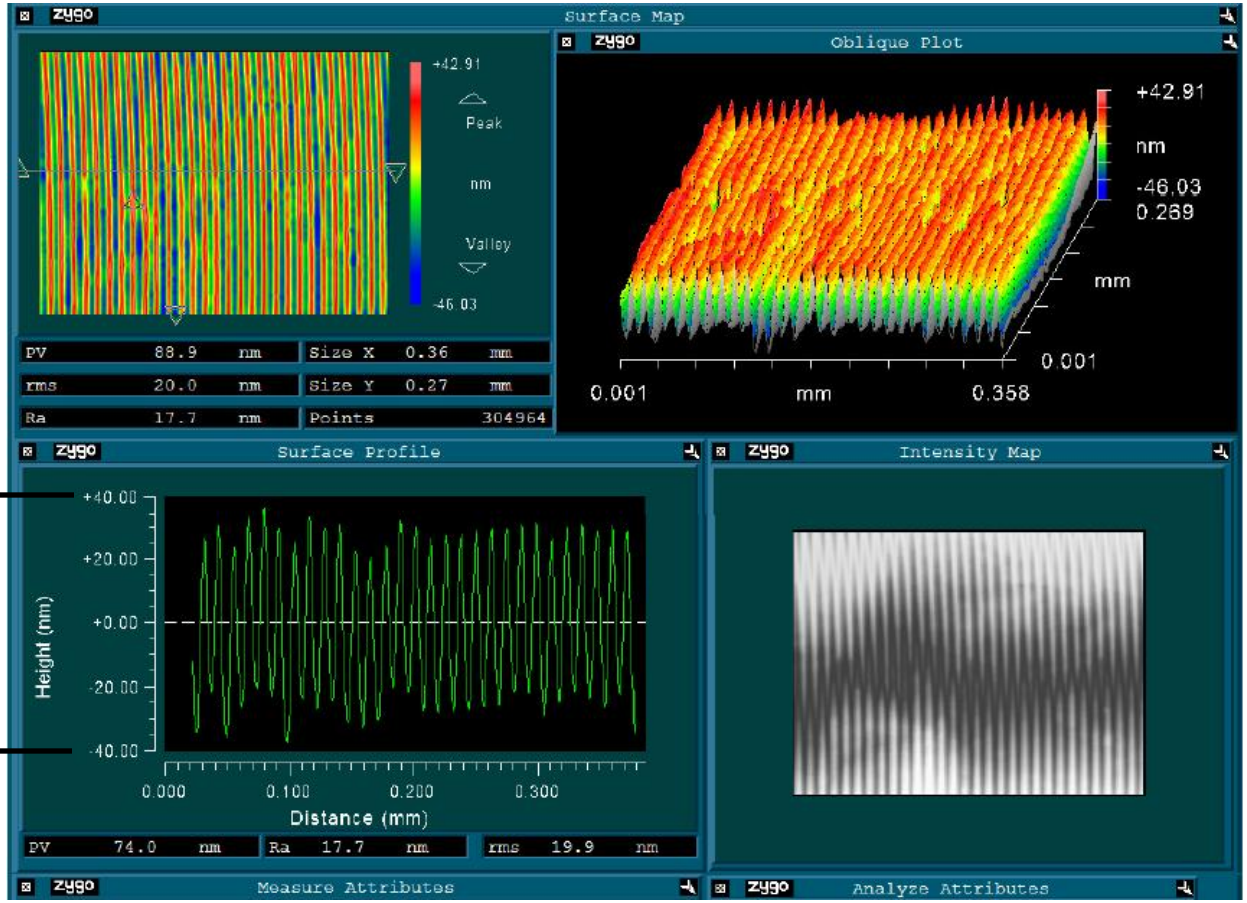
- VDL (NL) have machined and measured several cells –end cells. New!(recvd by CERN Oct 2010)
- Global profiles made with optical Zygo machine are illustrated for disk 24
- Design, tolerance bounds and achieved profile shown
- ETA of all cells –December 2010
- Bonding of complete structure by 1st quarter of 2011.



G. Riddone

4. Cell Qualification of CLIC_DDS_A

- Local profile made with an optical Zygo machine
- Local profiles indicate < 50nm variation in surface flatness
- Cell 24 displayed



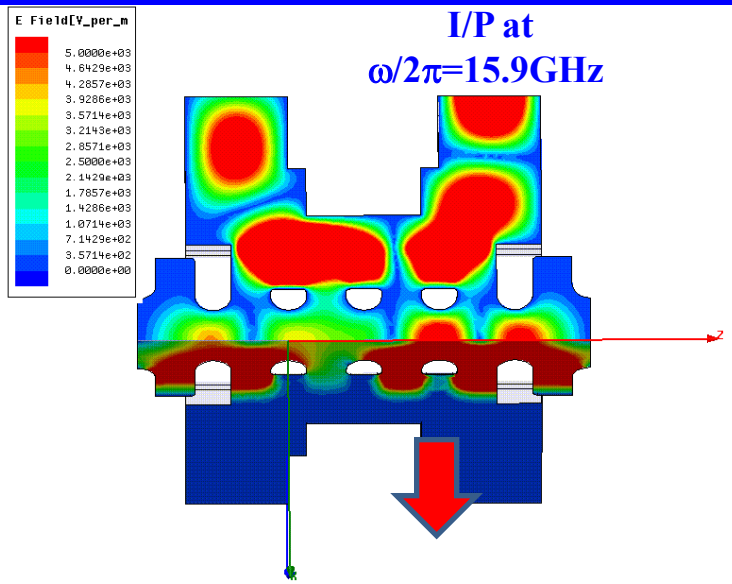
+40 nm

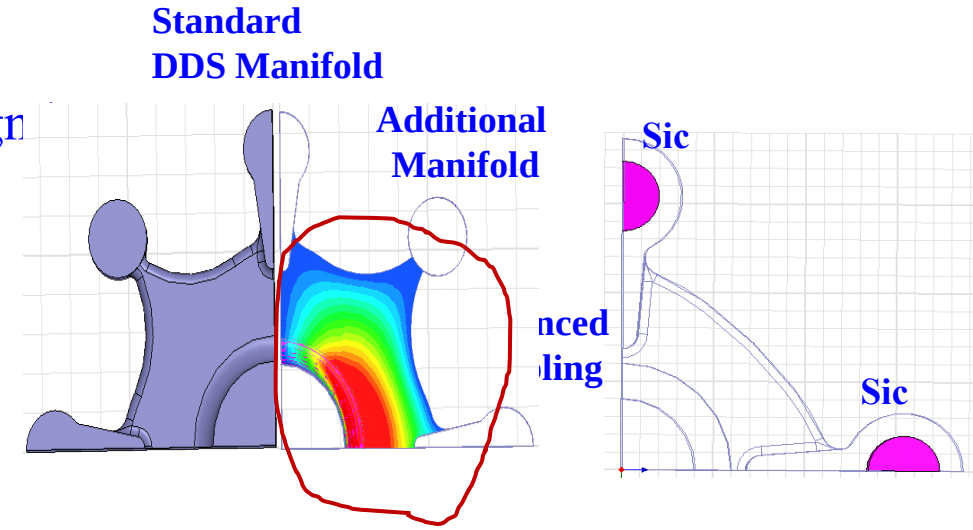
-40 nm

G. Riddone

5. Work in Progress/R&D Opportunities

- CLIC_DDS_A is equipped with mode launchers
- CLIC_DDS_B includes full HOM ports
- Initial studies on matching the HOM coupler for CLIC_DDS_B in progress (dipole band ~ 15.9 GHz – 18 GHz)
- Moving to a high phase advance (HPA) structure allows other parameters to be optimised
- 5π/6 phase advance structure design progress (for initial design see Linac2010)
- In the HPA design further features being explored
- Additional manifold (8)
- Influence of SiC rods on overall Q





5. Final Remarks

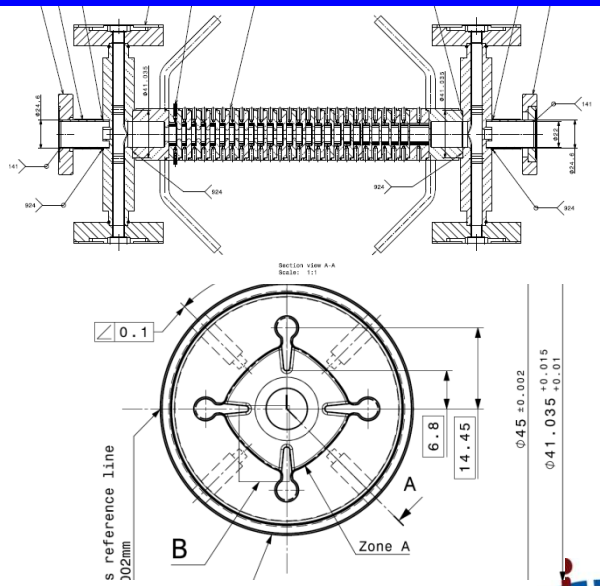
- **CLIC_DDS_A** : RF (including mode launcher matching cells) and mechanical design has been completed.
- Qualifications cells fabricated (VDL)–all cells by last quarter 2010
- Structure will be subsequently bonded in the first quarter of 2011, -- ready for high power testing in 2011 at the CLIC test stand.
- **CLIC_DDS_B**: Includes HOM couplers and interleaving. HOM coupler design in progress.
- New **CLIC_DDS R&D** in progress:
  - HPA: High phase advance design is being studied. It Allows optimisation of the remaining parameters –minimise surface fields, wakefields at stipulated v_g
  - Further optimisation is being explored by implementing additional manifolds and with the potential for the insertion of SiC rods to reduce the Q further

Acknowledgements

- I am pleased to acknowledge a strong and fruitful collaboration between many colleagues and in particular, from those at CERN, University of Manchester, Cockcroft Inst., SLAC and KEK.
- Several at CERN within the CLIC programme, have made critical contributions: W. Wuensch, A. Grudiev, I. Syrachev, R. Zennaro, G. Riddone (CERN).
- Thanks to Walter for arranging this session!

CLIC DDS Related Pubs.

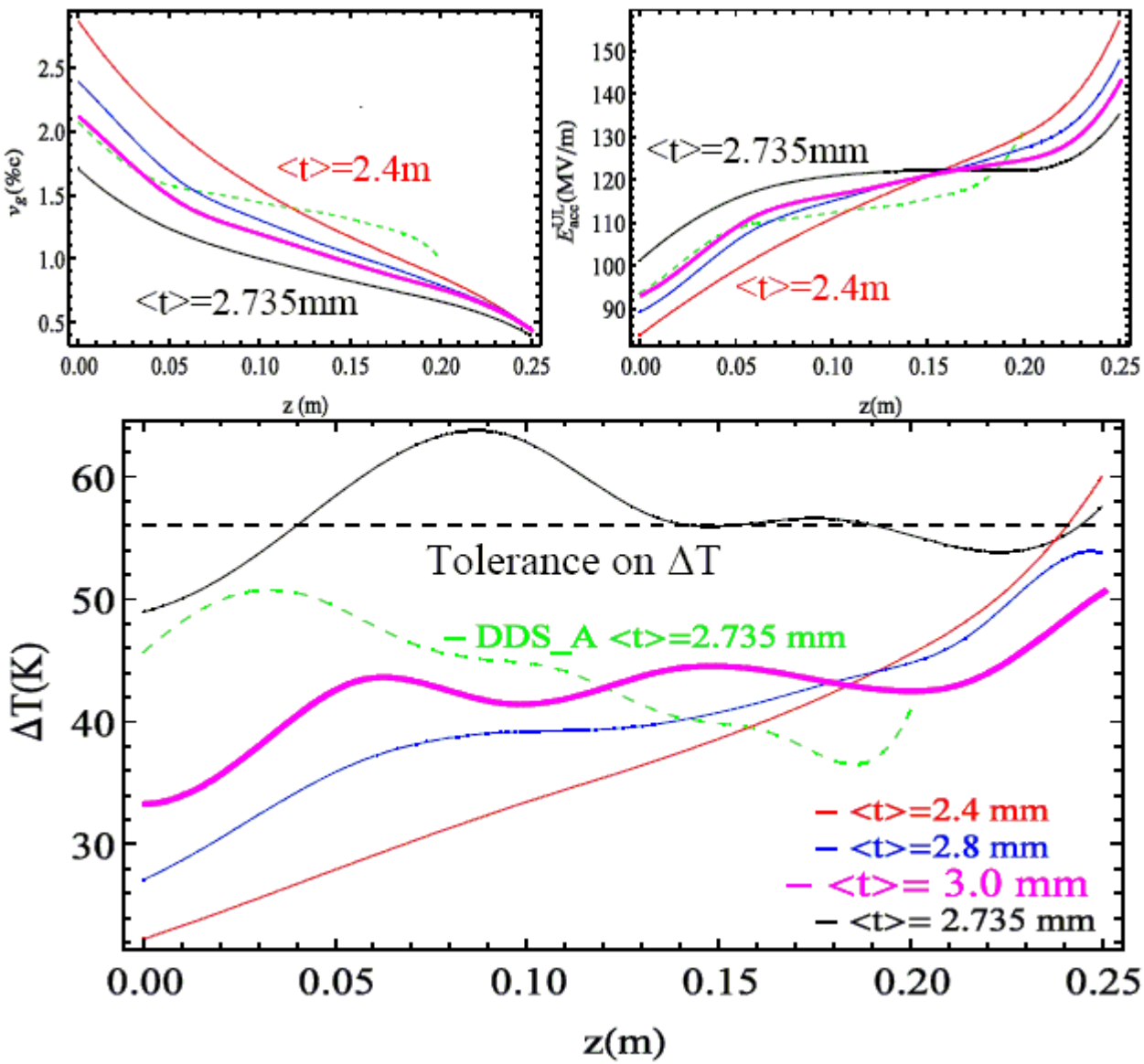
1. **R. M. Jones, *et. al*, PRST-AB, 9, 102001, 2006.**
2. **V. F. Khan and R.M. Jones, EPAC08, 2008.**
3. **V. F. Khan and R.M. Jones, LINAC08, 2008.**
4. **V. F. Khan and R.M. Jones, Proceedings of XB08, 2008.**
5. **R. M. Jones, PRST-AB, 12, 104801, 2009.**
6. **R. M. Jones, *et. al*, NJP, 11, 033013, 2009.**
7. **V. F. Khan and R.M. Jones, PAC09, 2009.**
8. **V. F. Khan, *et. al*, IPAC10, 2010.**
9. **V. F. Khan, *et. al*, LINAC10, 2010.**



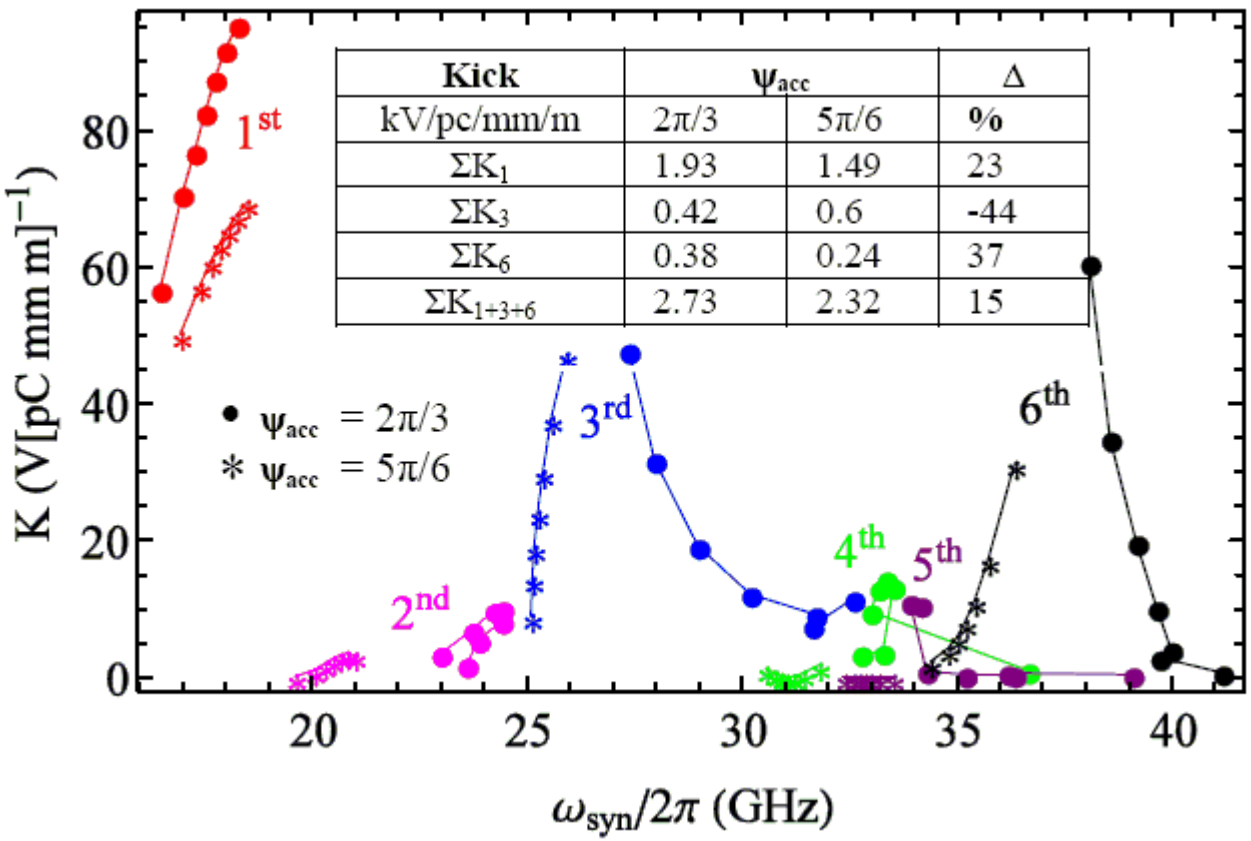
ICFA X-Band UK Workshop

- On the near horizon, December 2010, is the XB-10 workshop on accelerator structures, beam dynamics, and sources.
- Cockcroft Inst., UK
- Peer reviewed papers will be published in a NIMs A special issue.
- Registration is still open and, you are invited to attend!

5.RF parameters vs t



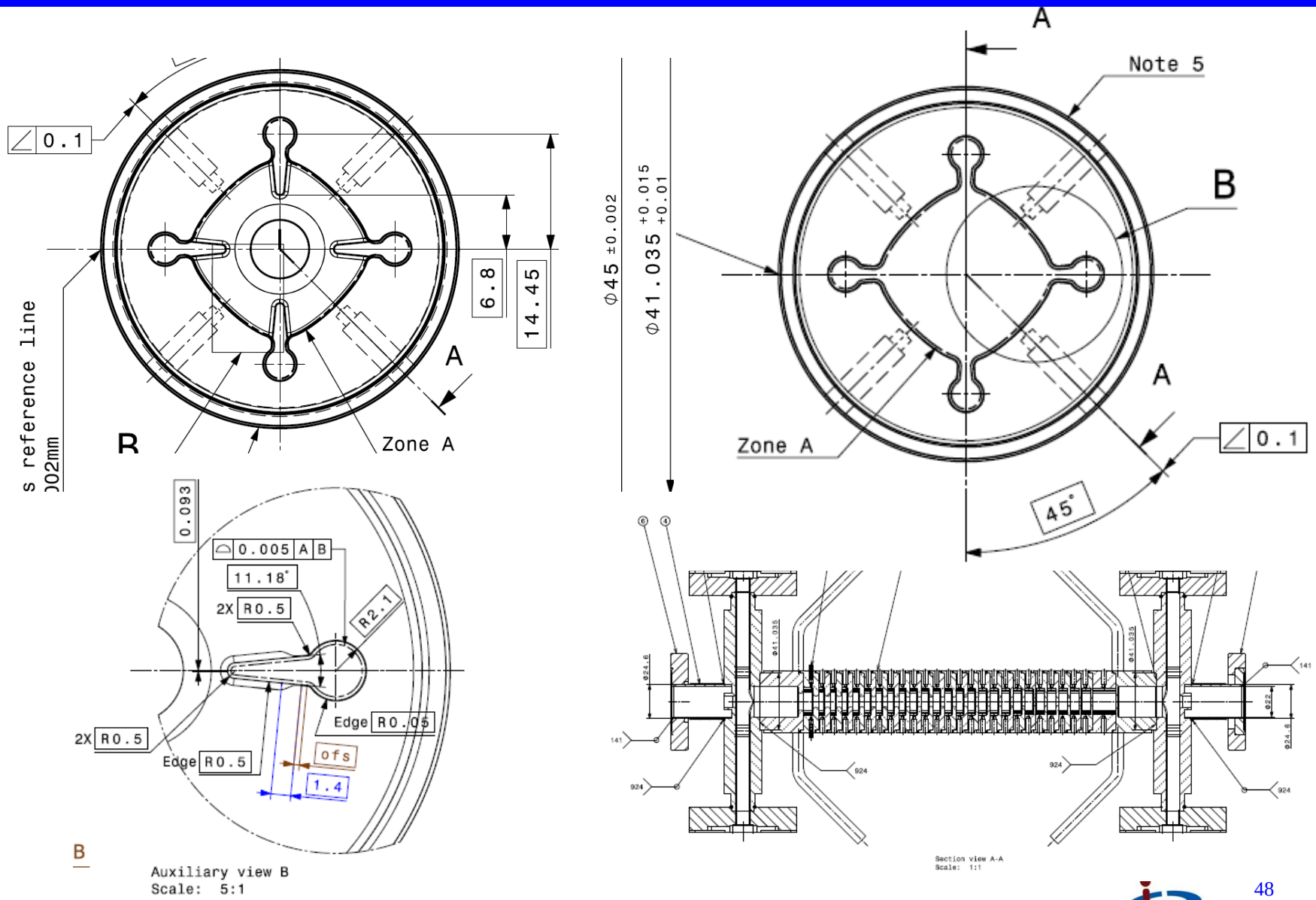
5.Kick factors for first six dipole



Kick	ψ_{acc}		Δ
kV/pc/mm/m	2π/3	5π/6	%
ΣK_1	1.93	1.49	23
ΣK_3	0.42	0.6	-44
ΣK_6	0.38	0.24	37
ΣK_{1+3+6}	2.73	2.32	15

Additional Slides!

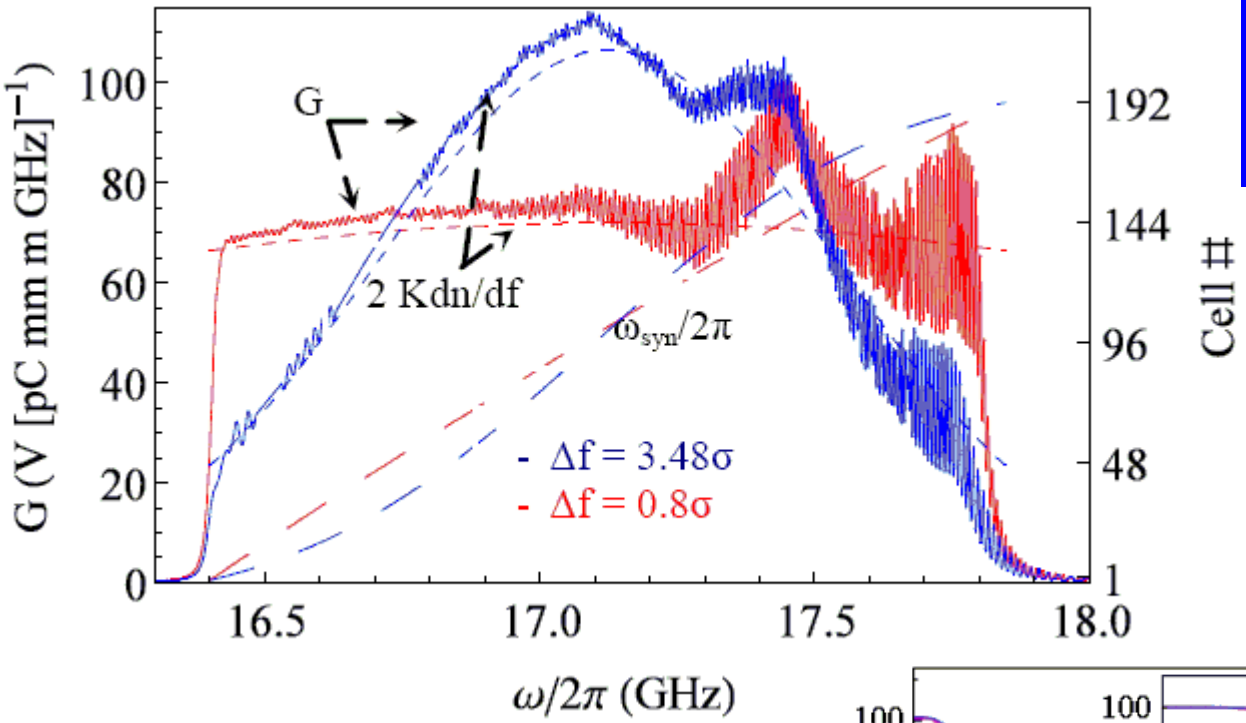
CLIC_DDS_A Mechanical Eng. Design



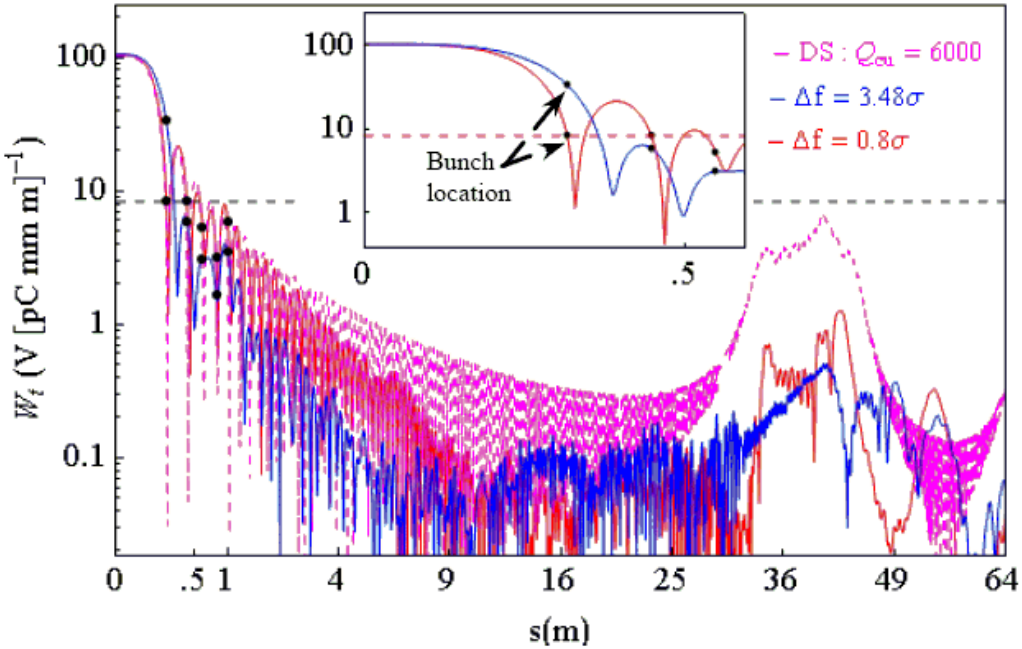
5. Comparison 2π/3 vs 5 π/6

RF parameters	Unit	DDS_A	DDS_HPA42	DDS_HPA32
Phase advance / cell	Deg.	**120**	**150**	**150**
Iris thickness	mm	**4/1.47**	**3.2/2.8**	**3.2/2.8**
Bunch population	10^9	**4.2**	**4.2**	**3.2**
Q (In / Out)	-	5020 / 6534	6931/7045	6931/7045
R' (In / Out)	MΩ/m	51 / 118	72.4/102.4	72.4/102.4
vg/c (In / Out)	%	2.07 / 1.0	2.1 / 0.45	2.1 / 0.45
$Eacc^{max}$ (L./UnL.)	MV/m	105 / 132	93 .3/ 143	90/ 138
P_{in}	MW	71	68.2	63.6
ΔT^{max}_{sur}	^oK	51	51	48
E^{max}_{sur}	MV/m	220	234	225
S_c^{max}	$W/\mu m^2$	6.75	5.9	5.5
RF-beam efficiency	%	23.5	29	23.3

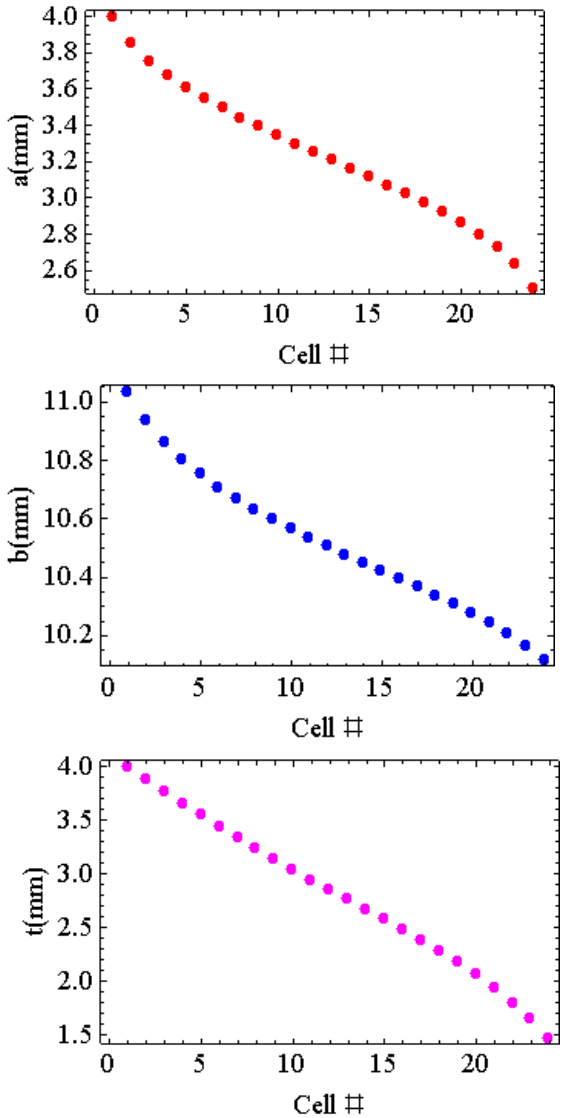
5. Spectral function

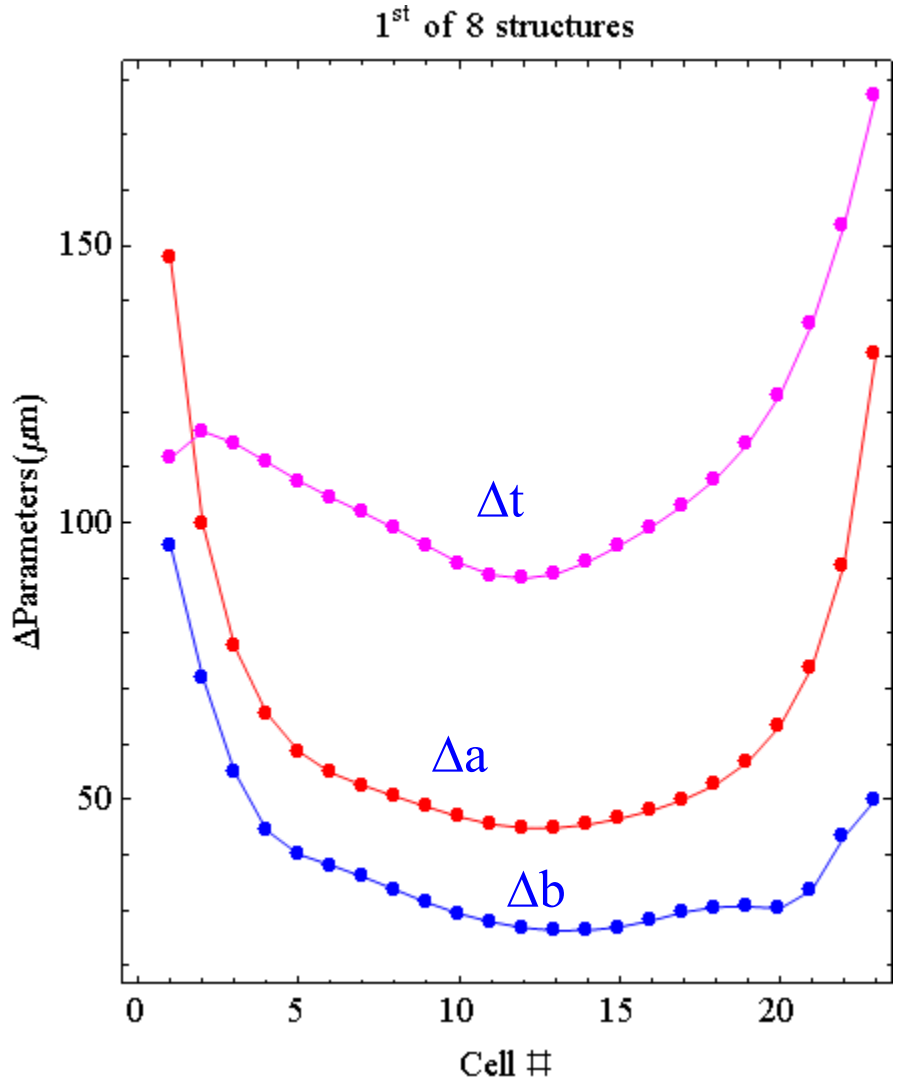


Wake function



CLIC_DDS_A Parameter Variation





CLIC_DDS_A Surface Fields