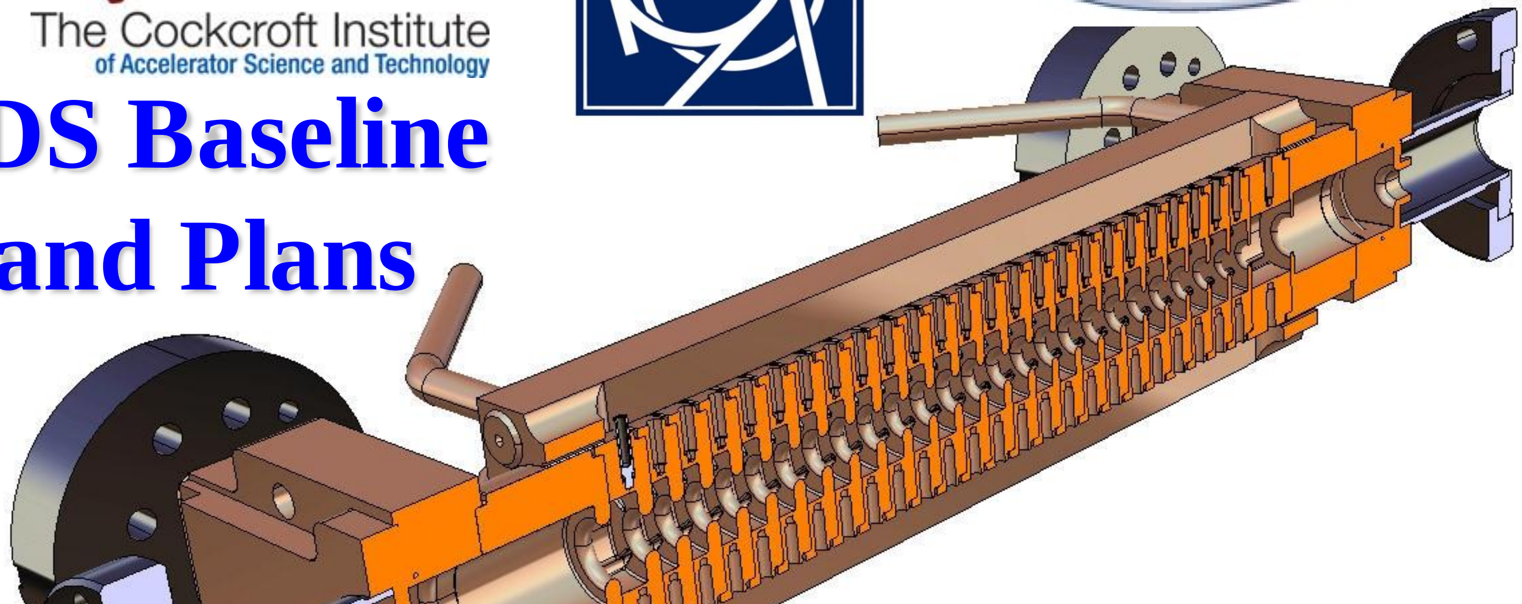
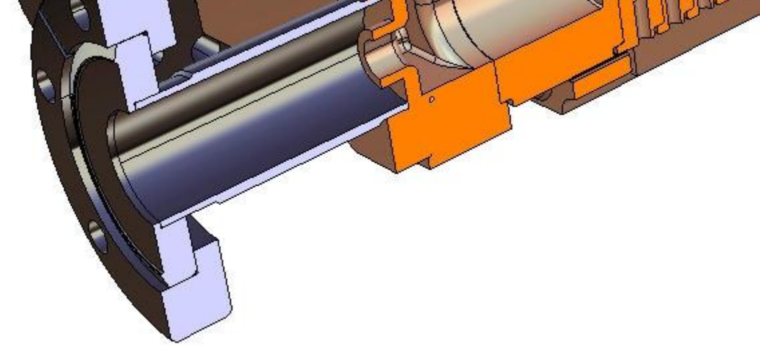
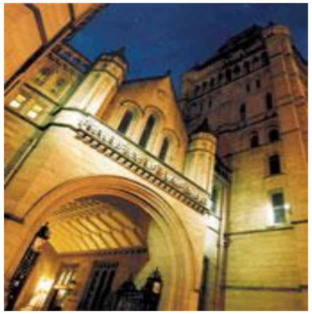
CLIC DDS Baseline Status and Plans



Roger M. Jones
Cockcroft Institute and
The University of Manchester

Wake Function Suppression & HG Research 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 Grad. April 2011, now CERN Fellow

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

I. Nesmiyan, CI/Univ. of Manchester PDRA.

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

L. Carver, Sept 2011 CI/Univ. of Manchester Ph.D. student

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

Overview

Entails:

1. **Suppressing long range transverse wakefield**
2. **Ensuring the e.m. surface fields (corresponding to accel. mode) are minimised**

Challenging!!

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.**

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.

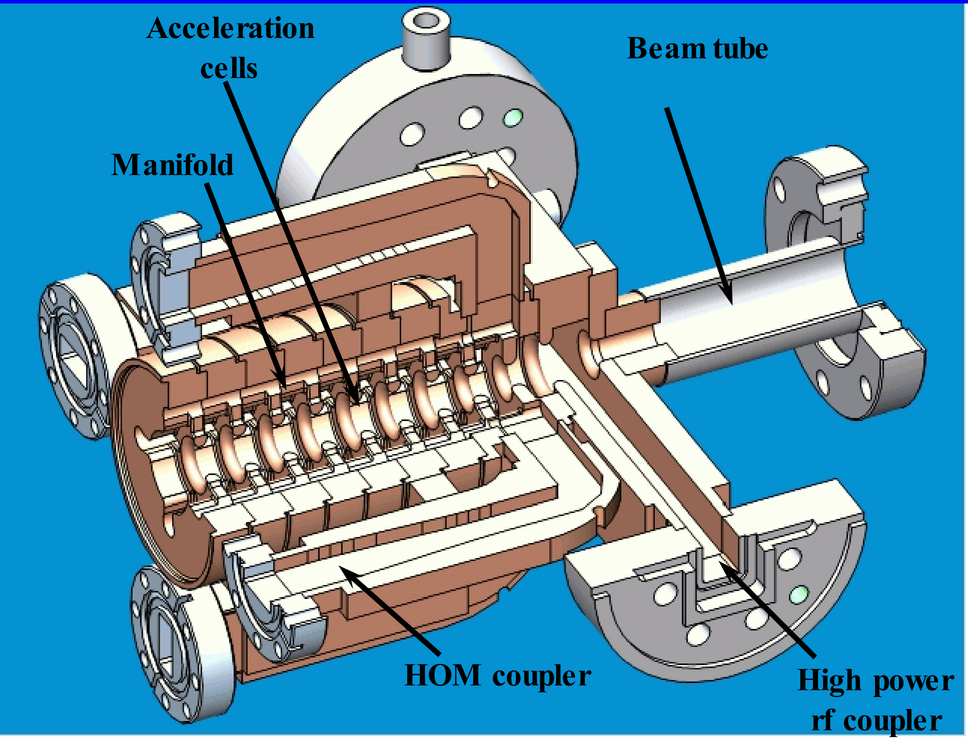
➢Choke mode suppression provides an alternative, but may negatively impact R_{sh} and can have a significant impact on breakdown

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

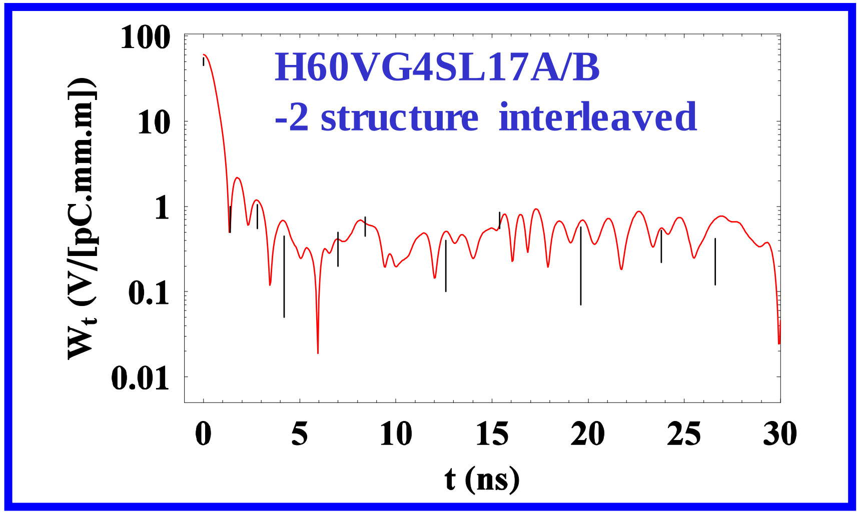
1. **Detuning the dipole bands by forcing the cell parameters to have a precise spread in the frequencies –presently Gaussian Kdn/df- and interleaving the frequencies of adjacent structures.**

2. **Moderate damping Q ~ 500-1000**

Features of CLIC DDS Linac

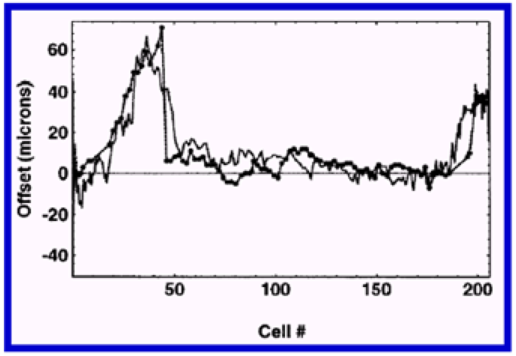


- NLC/G(J)LC SLAC/KEK RDDS structure (left) illustrates the essential features of the conceptual design
- Each of the cells is tapered –iris reduces (with an erf-like distribution –although not unique)
- HOM manifold running alongside main structure removes dipole radiation and damps at remote location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



Wake Suppression

- CMM (Coordinate Measurement Machine) data compared to ASSET power minimisation data remapped to frequency
- Dots indicate power minimisation



Remote Cell Alignment Diagnostic

CLIC Design Constraints

1) RF breakdown constraint

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

2) Pulsed surface temperature heating

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

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

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

Initial CLIC_DDS Designs

Three designs

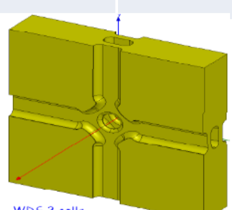
1. Initial investigation of required bandwidth to damp all bunches (~3GHz) –succeeds to suppress wakes, fails breakdown criteria!

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 ($\Delta f \sim 3.6\sigma \sim$ 13.75%) –SUCCESS (on suppressing wakes and meeting breakdown criteria)

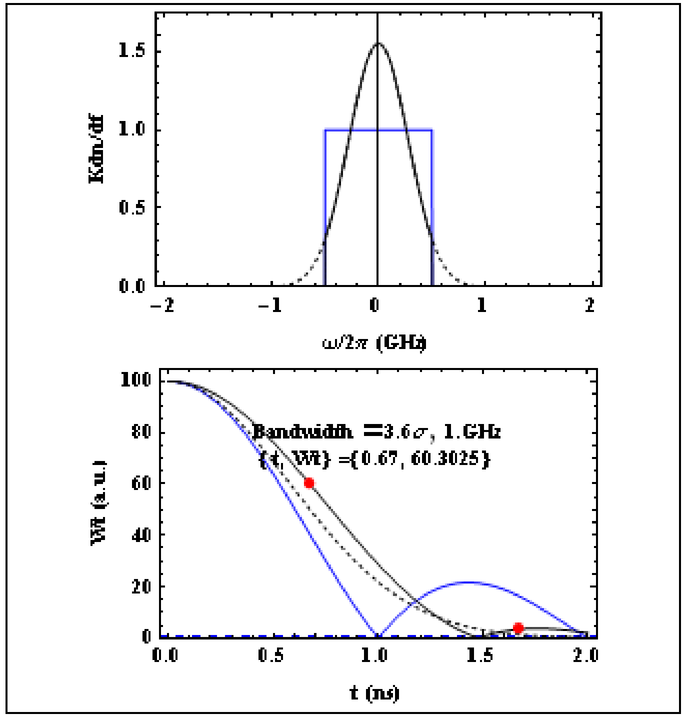
Initial CLIC_DDS Design –Δf determination

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

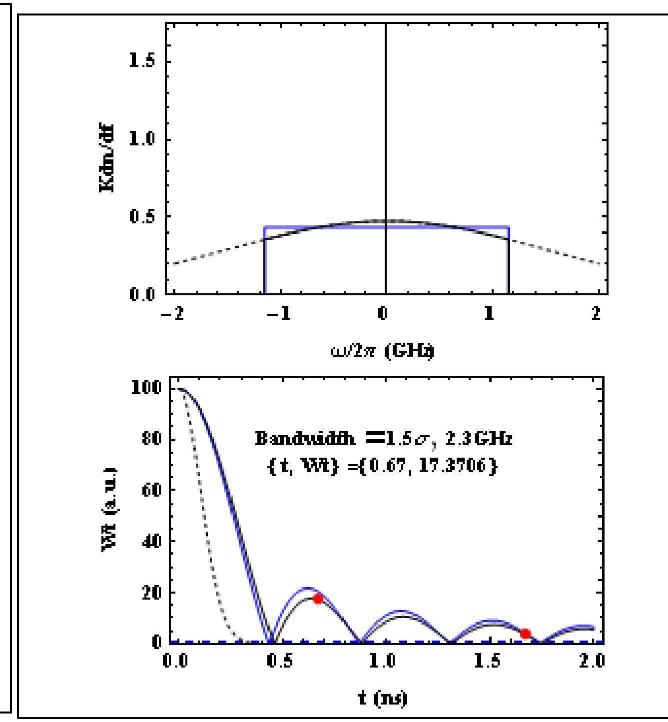


Lowest dipole
Δf~ 1GHz
Q~ 10

CLIC_G



Bandwidth Variation

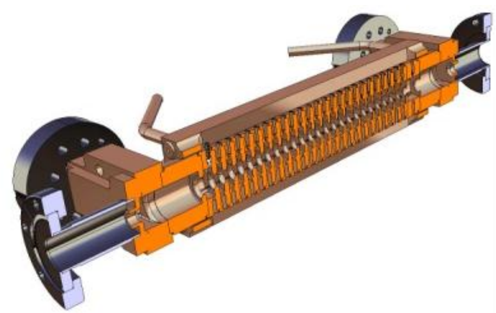


σ Variation

Truncated Gaussian :

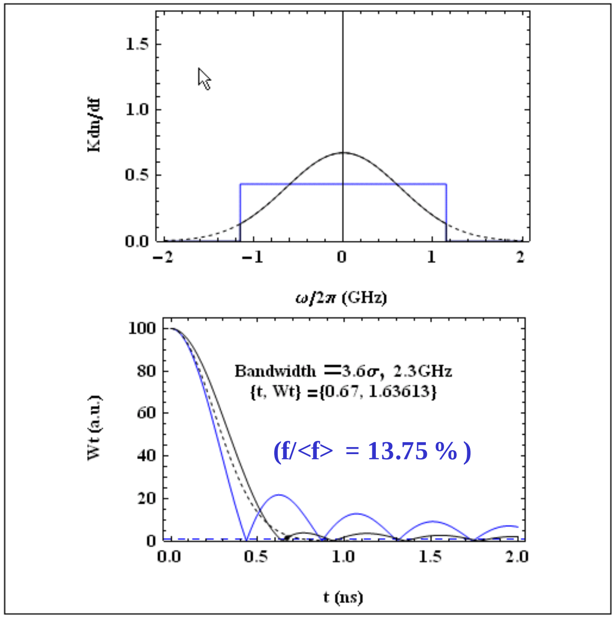
$$W_t = 2\bar{K}e^{-2(\sigma\pi t)^2}\left|\chi(t,\Delta f)\right|$$

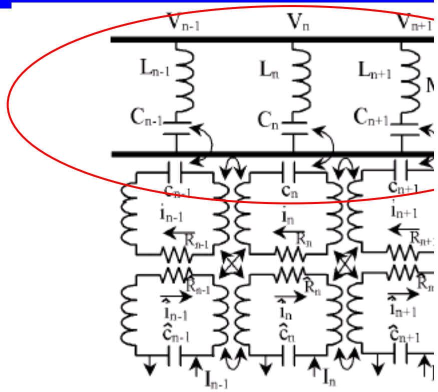
$$\text{where}: \chi(t,\Delta f) = \frac{\text{Re}\left\{\text{erf}\left(\left[n_\sigma - 4i\pi\sigma t\right]/2\sqrt{2}\right)\right\}}{\text{erf}\left(n_\sigma/2\sqrt{2}\right)}$$



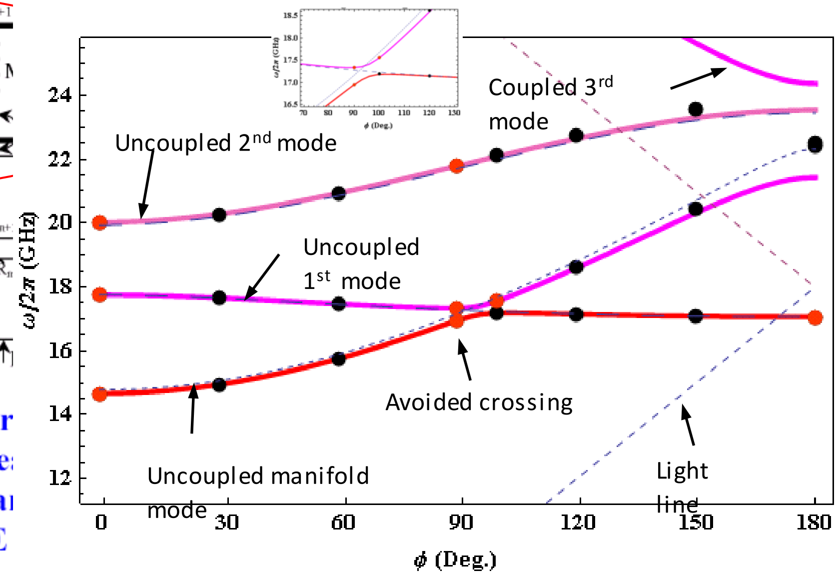
CLIC_DDS Uncoupled Design

Relaxed parameters tied to surface field constraints





Three cells in the chain ar
TM modes couple to the be
and TE modes and excited a
to the manifold is via TE
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

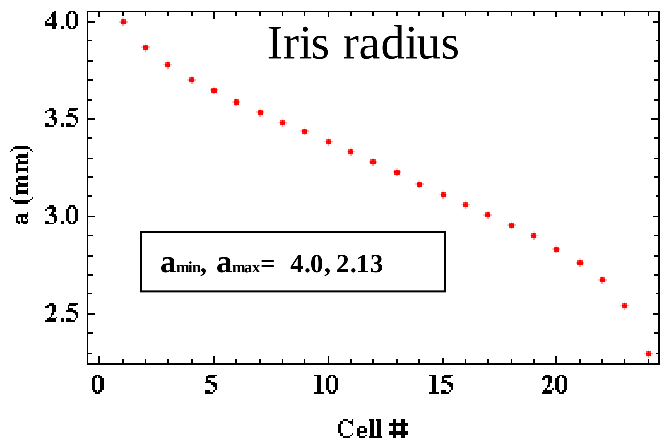
Cct Model Including Manifold-Coupling

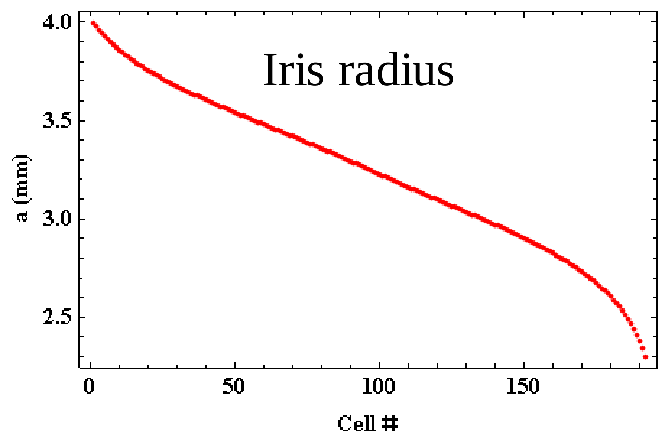
- ➢Spectral Function - including Manifold-Coupling, to calculate overall Wakefunction!
- ➢Not possible by other methods.

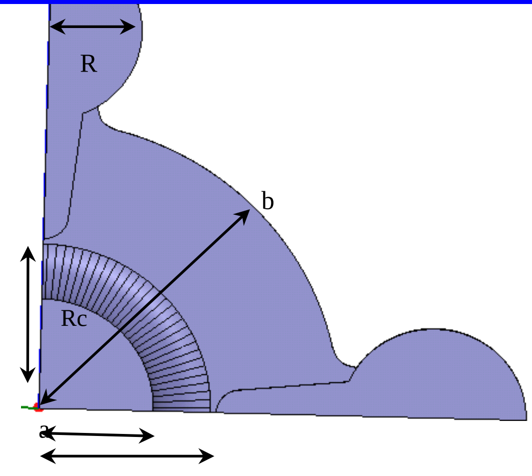
Mid-Cell

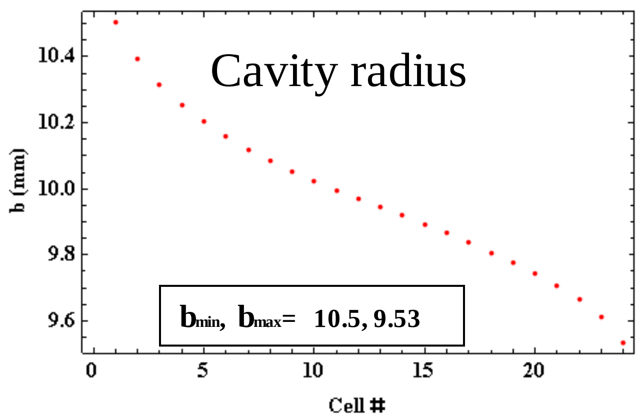
- ➢Dispersion curves for select cells are displayed (red used in fits, black reflects accuracy of model)
- ➢Provided the fits to the lower dipole are accurate, the wake function will be well-represented
- ➢Spacing of avoided crossing (inset) provides an indication of the degree of coupling (damping Q)

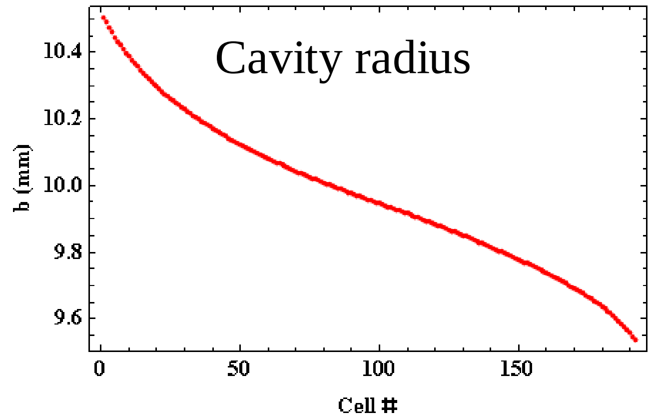
Structure Geometry: Cell Parameters

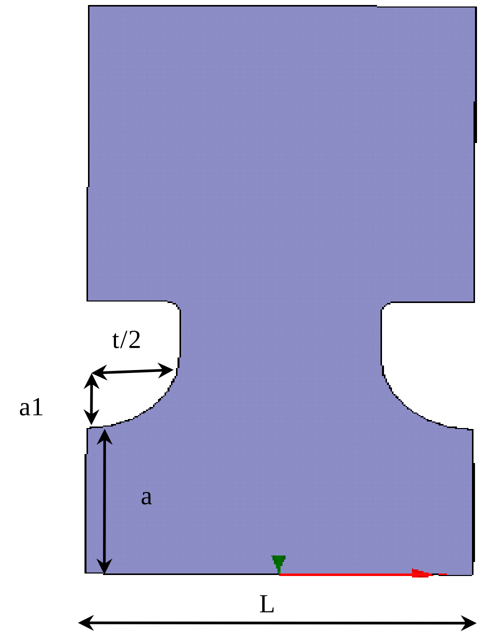












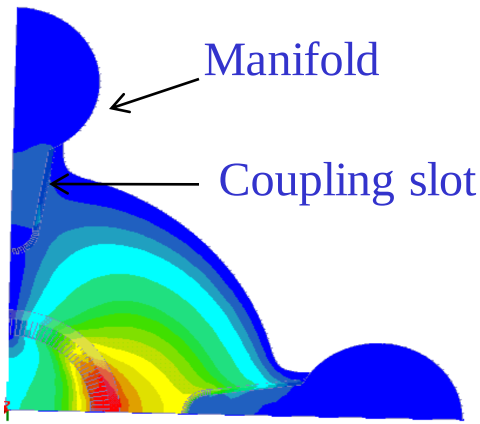
Sparse Sampled HPT (High Power Test)

Fully Interleaved 8-structures

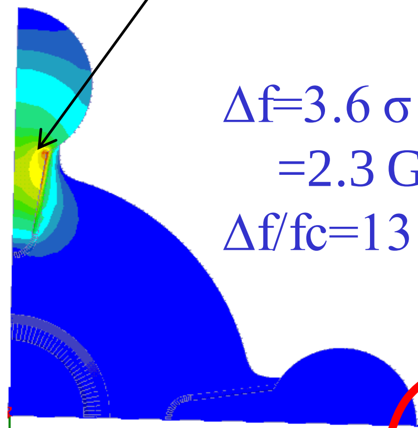
Summary of CLIC_DDS_C

The Cockcroft Institute
of Accelerator Science and Technology

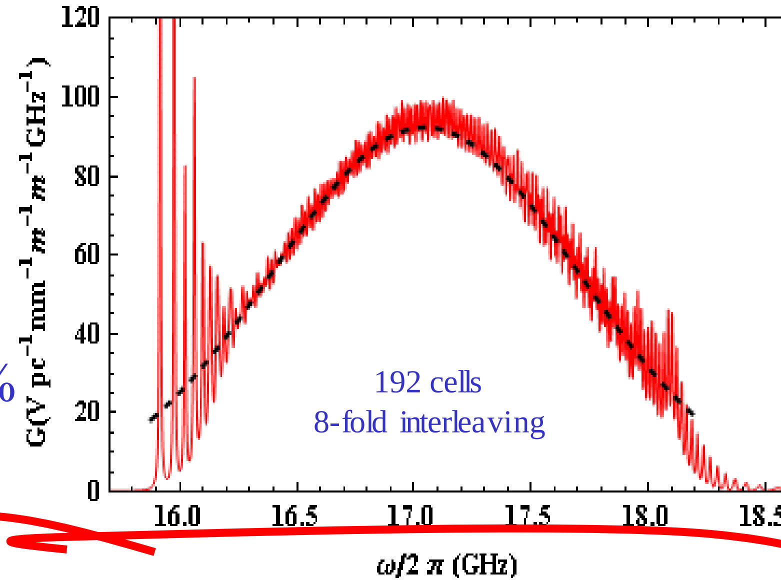
Dipole mode

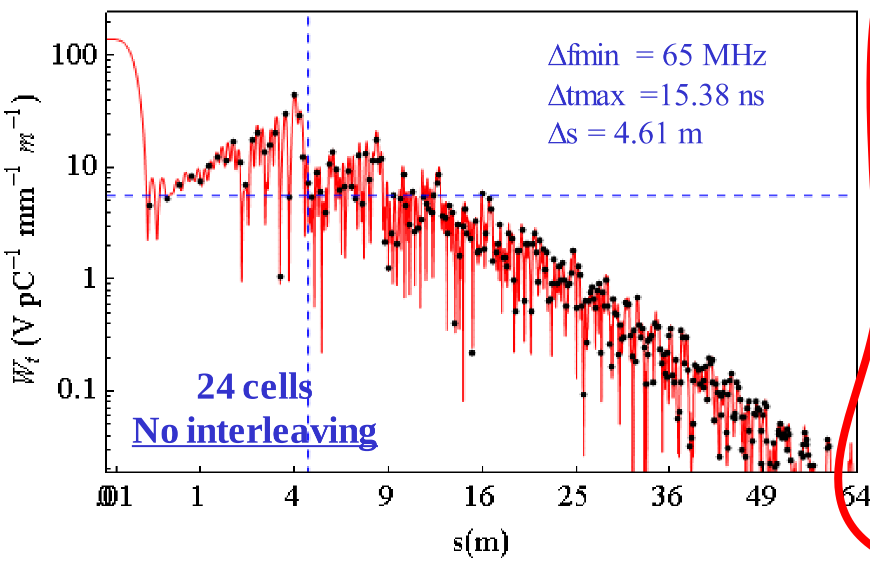


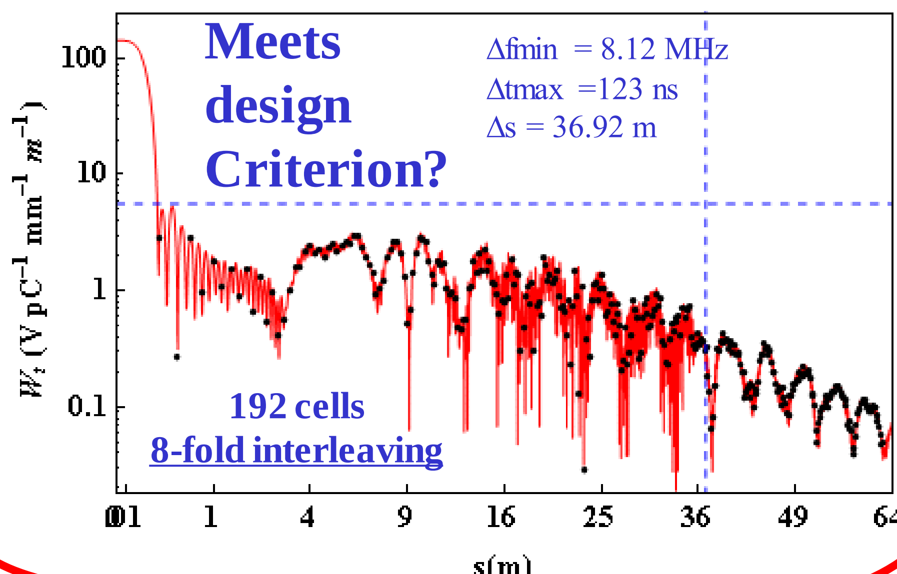
Manifold mode



$\Delta f = 3.6\ \sigma$
$= 2.3$ GHz
$\Delta f/fc = 13.75\%$







CLIC_DDS_E

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

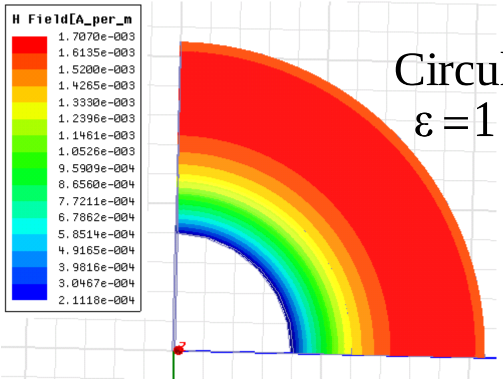
- Can the fields be redistributed such that a ~20% rise in the slot region is within acceptable bounds?
Modify cavity wall

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

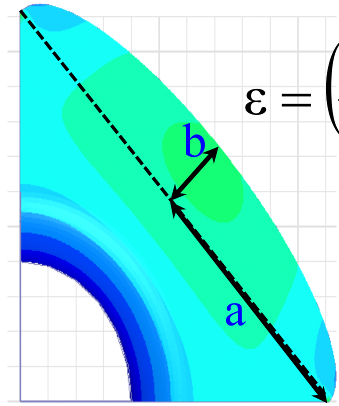
CLIC_DDS_E Elliptical Design –E Fields

The Cockcroft Institute of Accelerator Science and Technology

Single undamped cell
Iris radius=4.0 mm

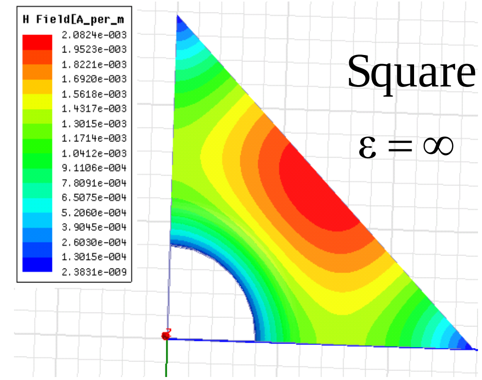


Circular $\varepsilon = 1$

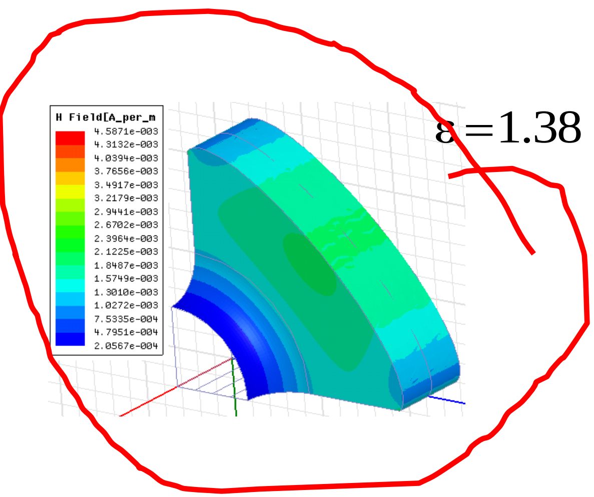


$$\varepsilon = \left(\sqrt{2} - 1\right)\frac{a}{b}$$

Convex ellipticity



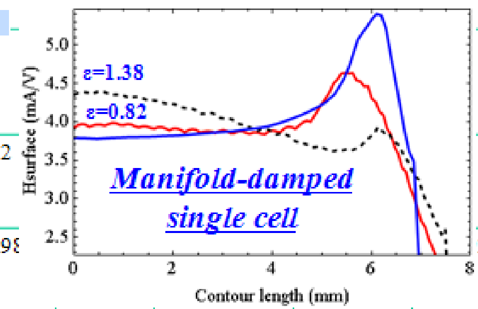
Square $\varepsilon = \infty$



$\varepsilon = 1.38$

	Circular	Rectangular	Elliptical (Convex)	0						
ε of cavity	1	∞	4.14	2.07	1.38	0.82				
f_{acc}(GHz)	12.24	12.09	11.98	12.0	11.99	11.98				35
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

0



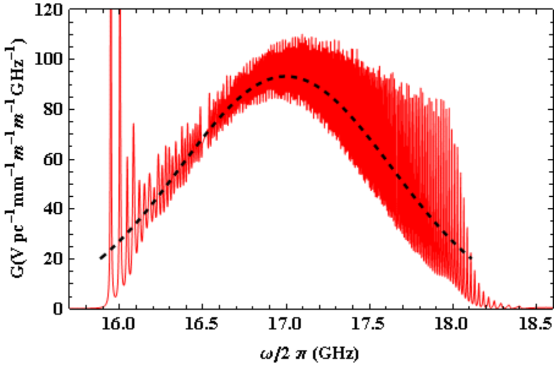
Iris radius = 4. 0 mm
Iris thickness = 4.0 mm

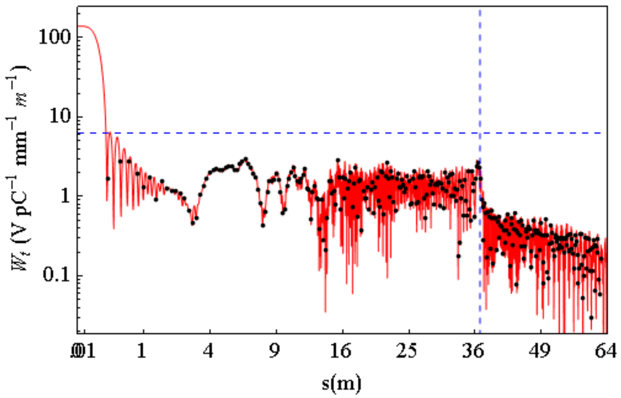
0 **Chosen design**

R.M.

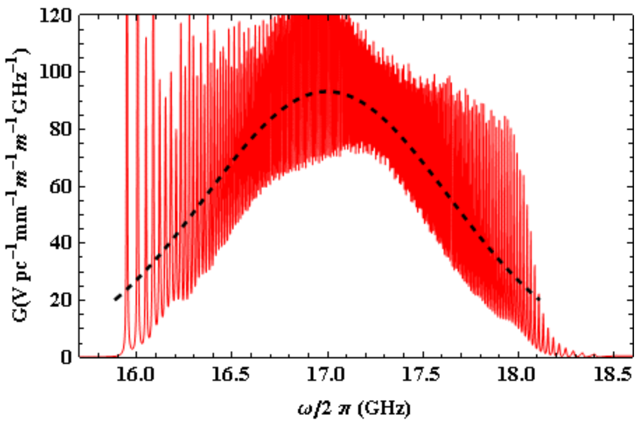
CLIC_DDS_E vs CLIC_DDS_ER Wakefield

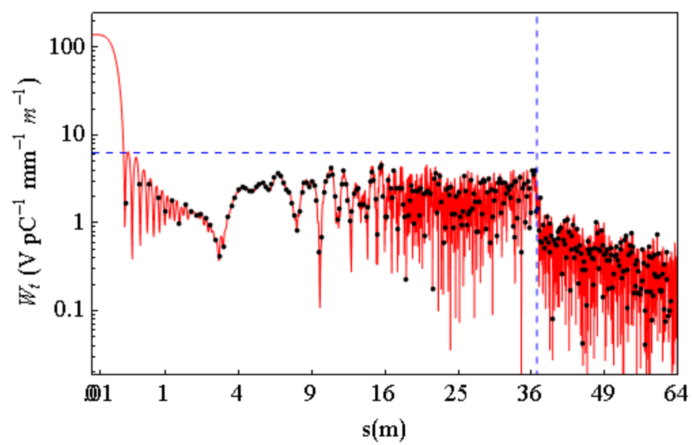
Spectral Function **Wakefunction**





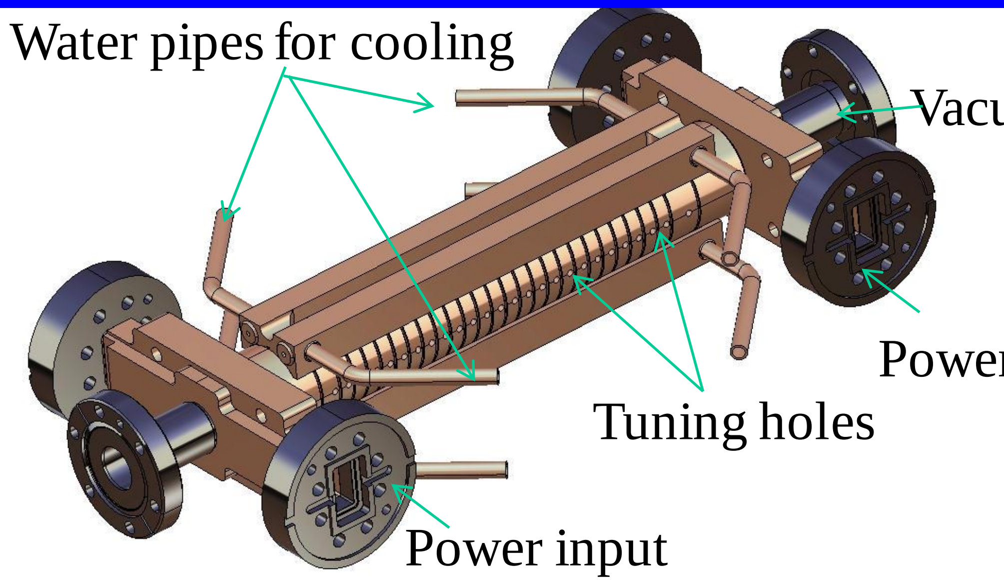
CLIC_DDS_E :Rc=6.2 - 6.8 mm (optimised penetration)

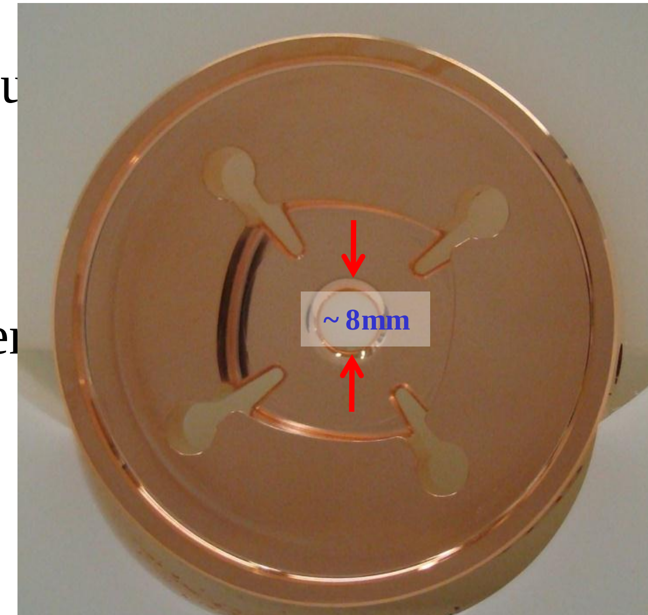




- **CLIC_DDS_ER : Rc=6.8 mm const (a single one of these structures constitutes CLIC_DDS_A, being built for HP testing)**
- **Wakefield suppression is degraded but still within acceptable limits.**

Mechanical Eng. Design of DDS_A





- **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**
- **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**

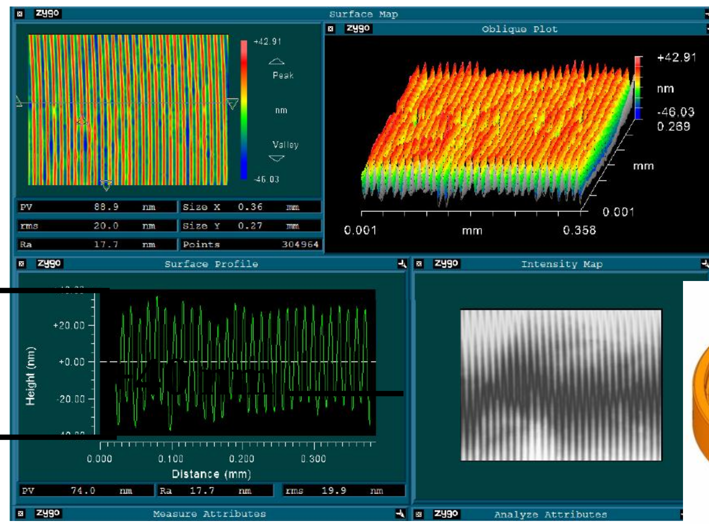
- **<u>Qualification cells complete!</u>**
- **Metrology and bonding of 4-cell stack tested at CERN**
- **Encouraging results**

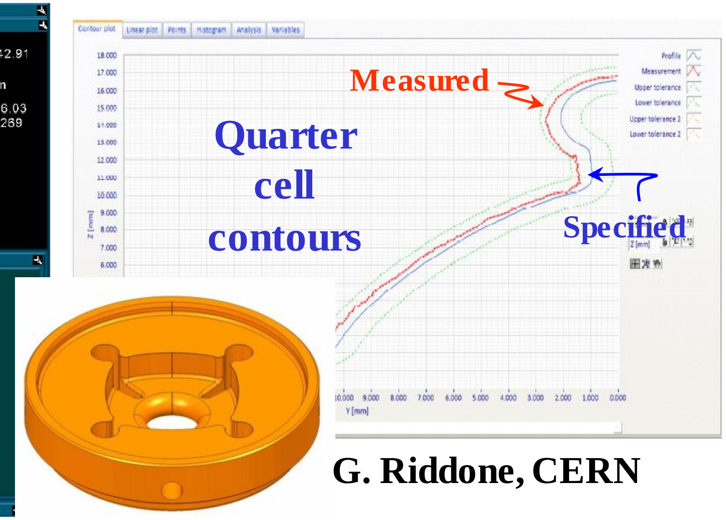
G. Riddone, V.Soldatov, CERN

Cell Qualification of CLIC_DDS_A

- VDL (Netherlands) have machined and measured several cells –end cells. (recvd by CERN Oct 2010)
- Global profiles made with optical Zygo machine are illustrated for disk 24
- Design, tolerance bounds and achieved profile shown

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





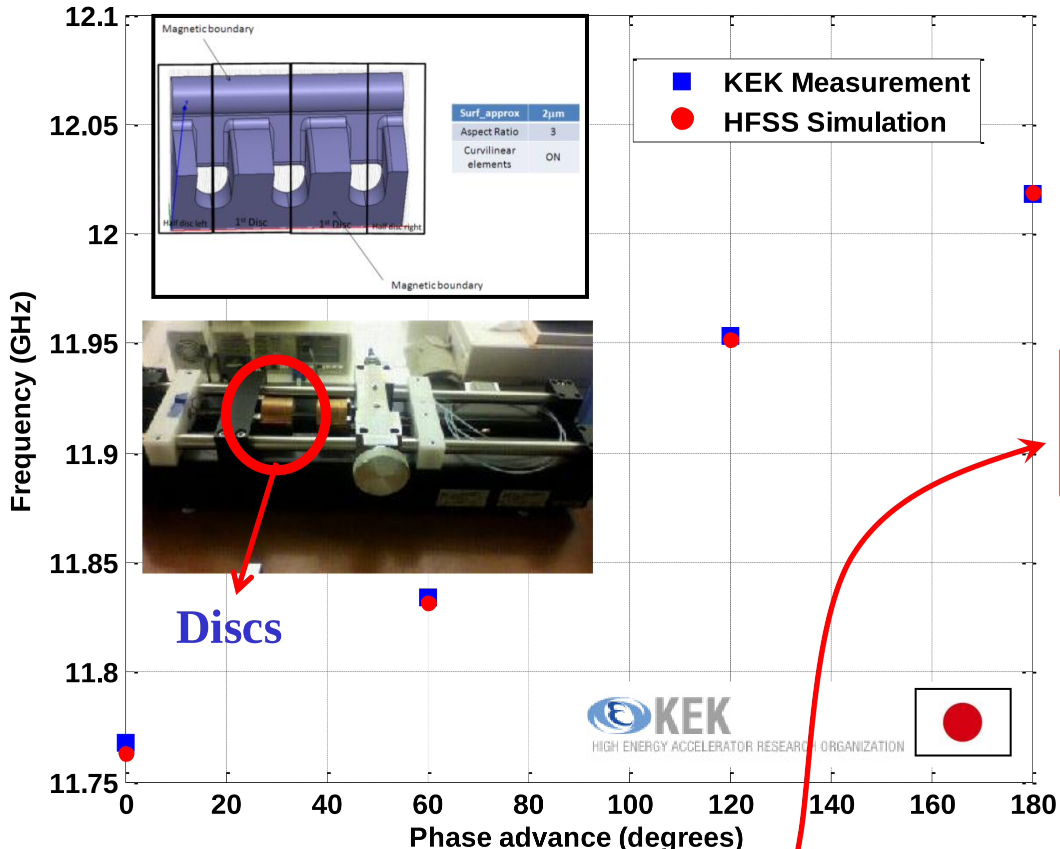
G. Riddone, CERN

- <u>We are now using Morikawa (Japan) to fabricate cells –rf test at KEK and CERN</u>
- <u>Fabrication and bonding of complete structure by end of Jan 2012</u>
- <u>HP test of structure in 2012?</u>

Fabrication Status of CLIC_DDS_A

- **MORIKAWA, under direction of KEK (T. Higo), has produced 5 disks - cold RF measurements and metrological control performed in November 20**
- **Initial measurements on cells performed at KEK (T. Higo)**
- **Five, in principle, identical cells delivered to CERN together with two half cells to be used for measurements –for further measurements a CERN**
- **Cells now completed metrological control**
- **Stack setup for RF measurements built at CERN (next slide)**
- **Measurements made in November 2011**
- **Full production of all cells going ahead in December –expect final bonded structure by end of Jan 2012 (revised June 2012)**

First Comparison Between KEK Measurements & Simulations on Morikawa Cells



	HFSS*	KEK	Δ
Mode 0 (MHz)	11762.8	11767.5	-4.7
Mode π/3 (MHz)	11831.6	11833.75	-2.15
Mode 2π/3§ (MHz)	11951.7	11953.75	-2.05
Mode π (MHz)	12019.0	12018.437	0.6

* HFSS scaled in air using ε_r=1.000618

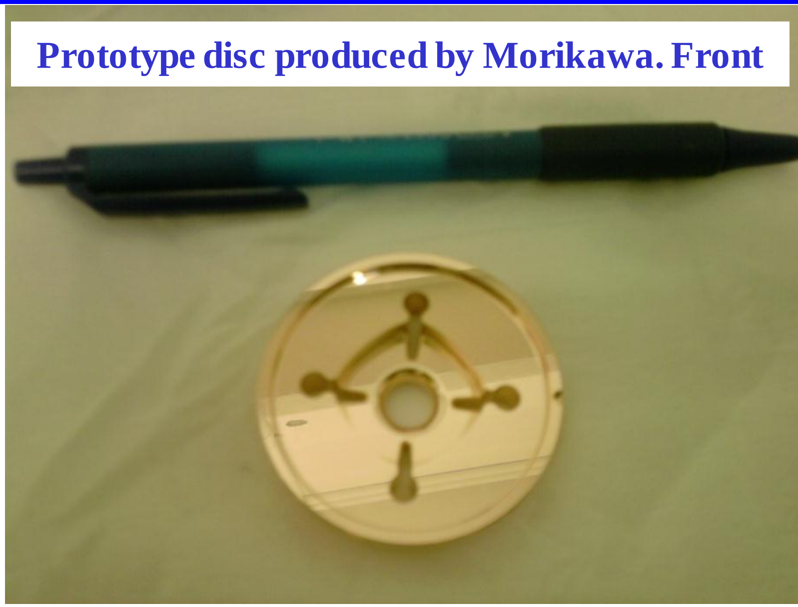
§This cell is the *actual* cell –non-symmetrical and equipped with an averaging of b. This explains the difference in the frequency from the nominal value of 11994.6MHz

Tuning range ~20MHz

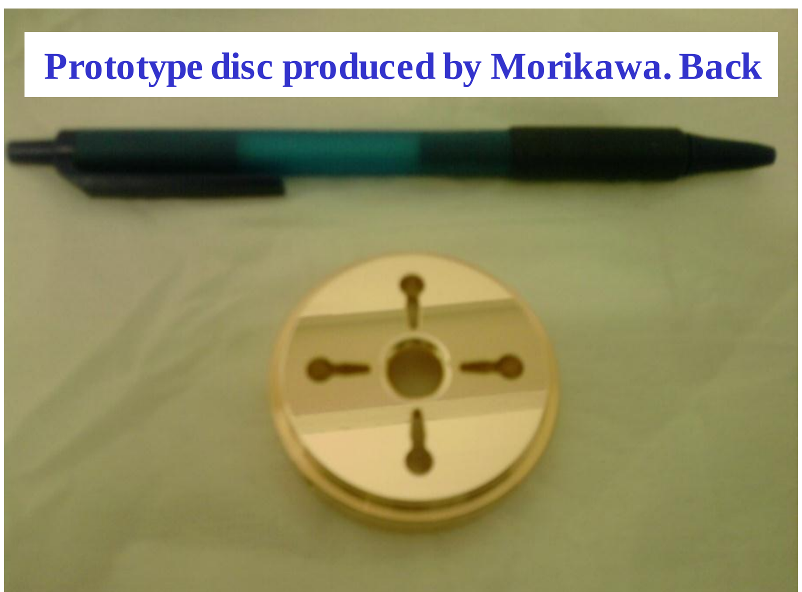
Indicative of ~2 µm fab tolerance!

Measurements at CERN

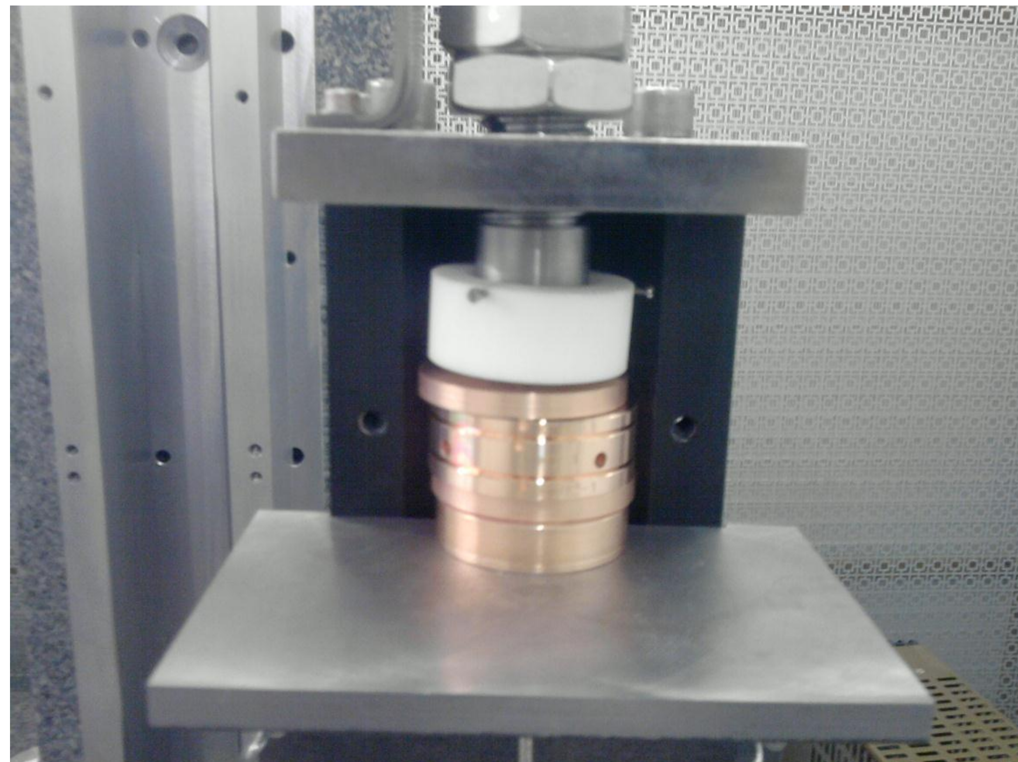
Prototype disc produced by Morikawa. Front



Prototype disc produced by Morikawa. Back



European Organization for Nuclear Research



November CLIC_DDS_A Disks ready for RF measurements at CERN!

CLIC_DDS_A Measurements at CERN

Prototype disc produced by Morikawa under metrological control

➢A stack of 7 discs in total (5 regular discs + 2 halves) at CERN were submitted to:

1. Metrological assessment
2. RF cold measurements both for Monopole and for first Dipole Band.

➢Production of 26 discs (24 regular discs+2 Matching disks) initiated in Japan in December.

➢ Expected delivery date for complete set the discs, is end of January (revised to June)

Beam Dynamics

Direct Effect

- **Assumes bunches are effected one- on-one –usual assumption for many years!**
- ***a* is a matrix which describes the wake**
- **In addition for CLIC_G Q ~ 10 and this effectively enables W_t to be neglected after to nearest neighbours**

Indirect Effect

- **Assumes bunches are influenced by succeeding bunches –many bunch coupling**

Ref: D. Schulte: PAC09, FR5RFP055; PRST-AB 14,084402 (2011)

Bunch k kicks j: $y_j = a_{j-k} y_k$

$$a_{j,k} = \begin{cases} \dfrac{L W_t\left(z_j - z_k, s\right) N e^2}{2 k_b E(s)} & \forall\, j > k \\ 0 & \forall\, j \le k \end{cases}$$

L is the cell length, s is the distance down linac,

N is the number of particles per bunch, k_b is betatron focussing and E is the energy

At end of linac all bunches in a matrix:

$$y_f = (1 + a) y_i$$

Beam Dynamics

Indirect Effect

- **Straightforward to build this up in an iterative process for m bunches –each bunches communicates with its neighbour and this ripples down the chain**
- **Figures of merit:**
  F_c representative of coherent oscillations of the train -the rms over the whole train
  F_{rms} the bunch to bunch rms

$$F_c = \frac{1}{n}\sum_k \left|\sum_j A_{kj}\right|^2$$

$$F_{rms} = \frac{1}{n}\sum_{k=0}^{n-1}\sum_{j=1}^{k}\left|A_{j,k}\right|^2$$

$$y_f = \left(1 + \frac{a}{m}\right)^m y_i$$

In the limit of an infinite number of bunches

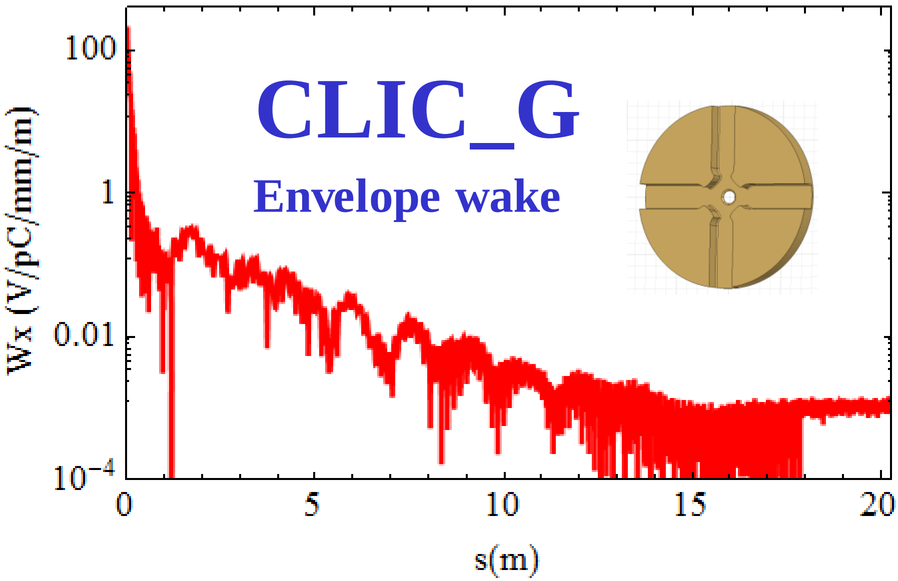
$$y_f = A y_i$$
$$A = \exp(a)$$

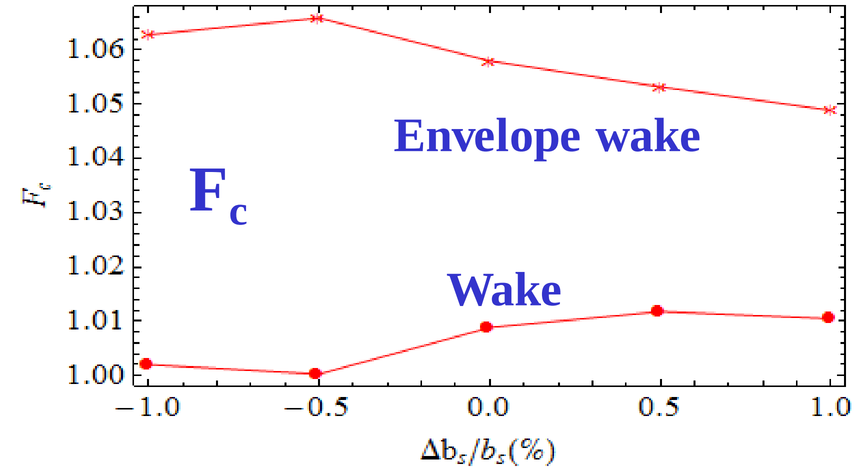
Returning to a finite number of bunches Taylor expand:

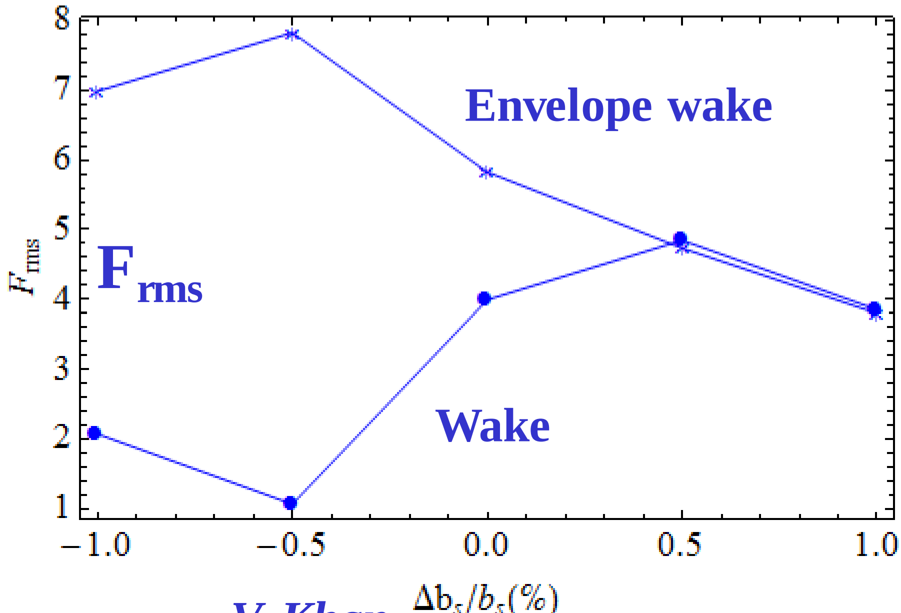
$$A = \sum_{k=0}^{\infty}\frac{a^k}{k!} = \sum_{k=0}^{n-1}\frac{a^k}{k!}$$

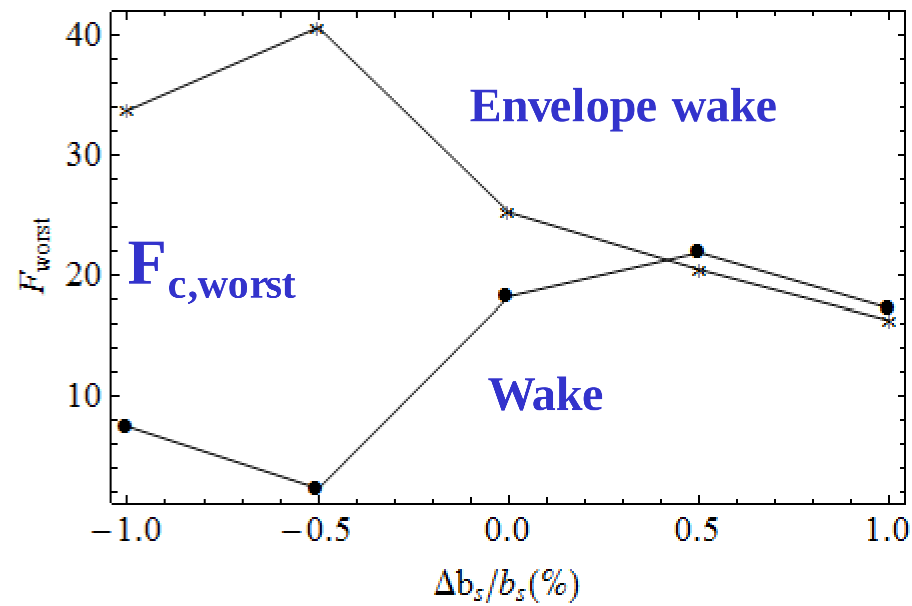
$$\left(a^n = 0 \text{ since } a_{jk} = 0 \;\forall\; j \le k\right)$$

Beam Dynamics



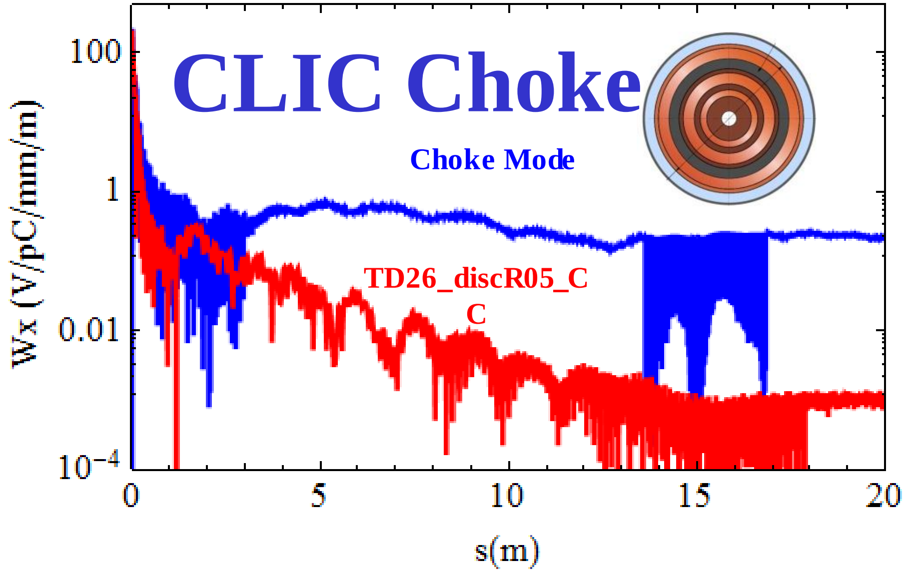


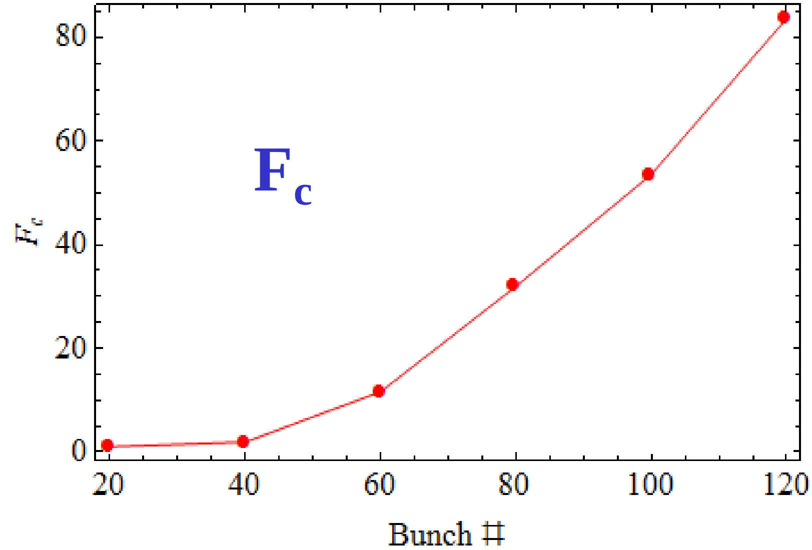


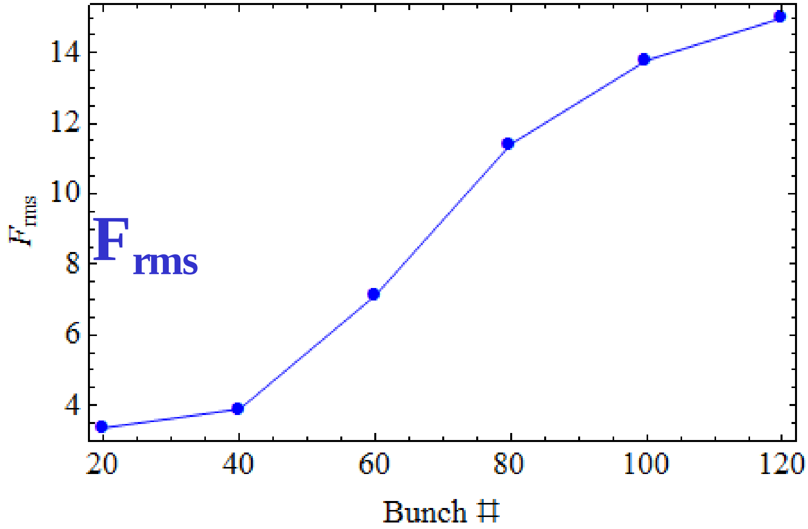


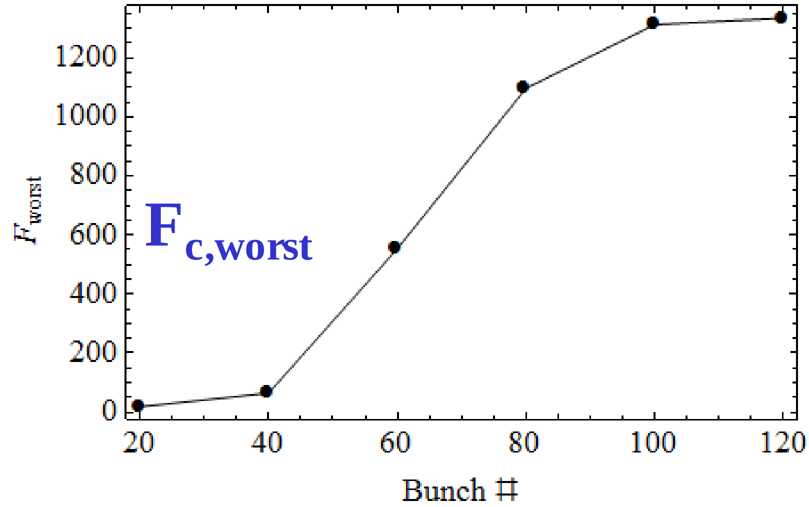
V. Khan

Beam Dynamics





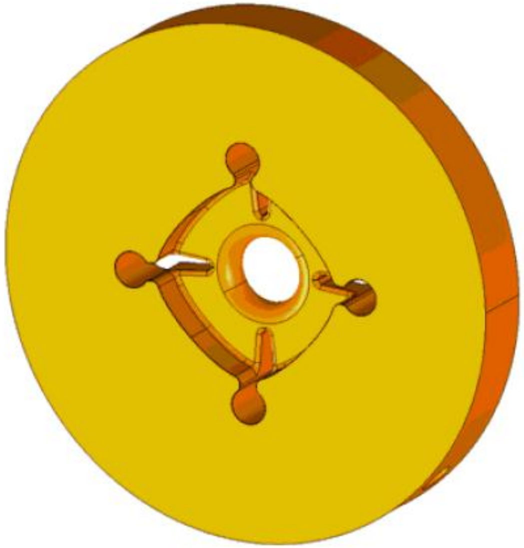


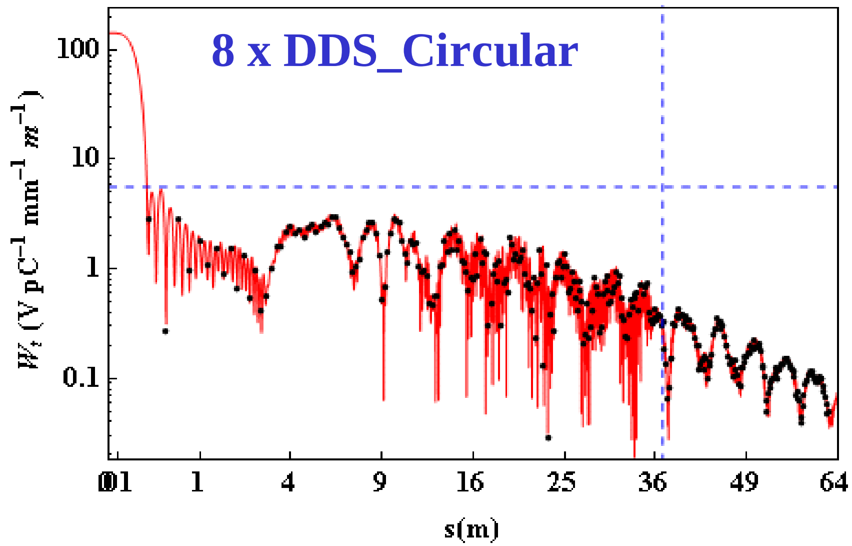


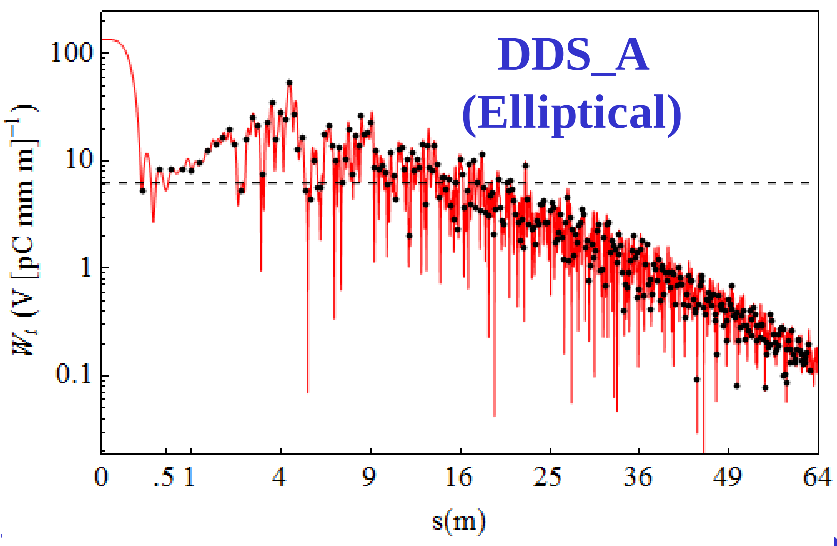
J. Shi, V. Khan

Beam Dynamics

CLIC_DDS



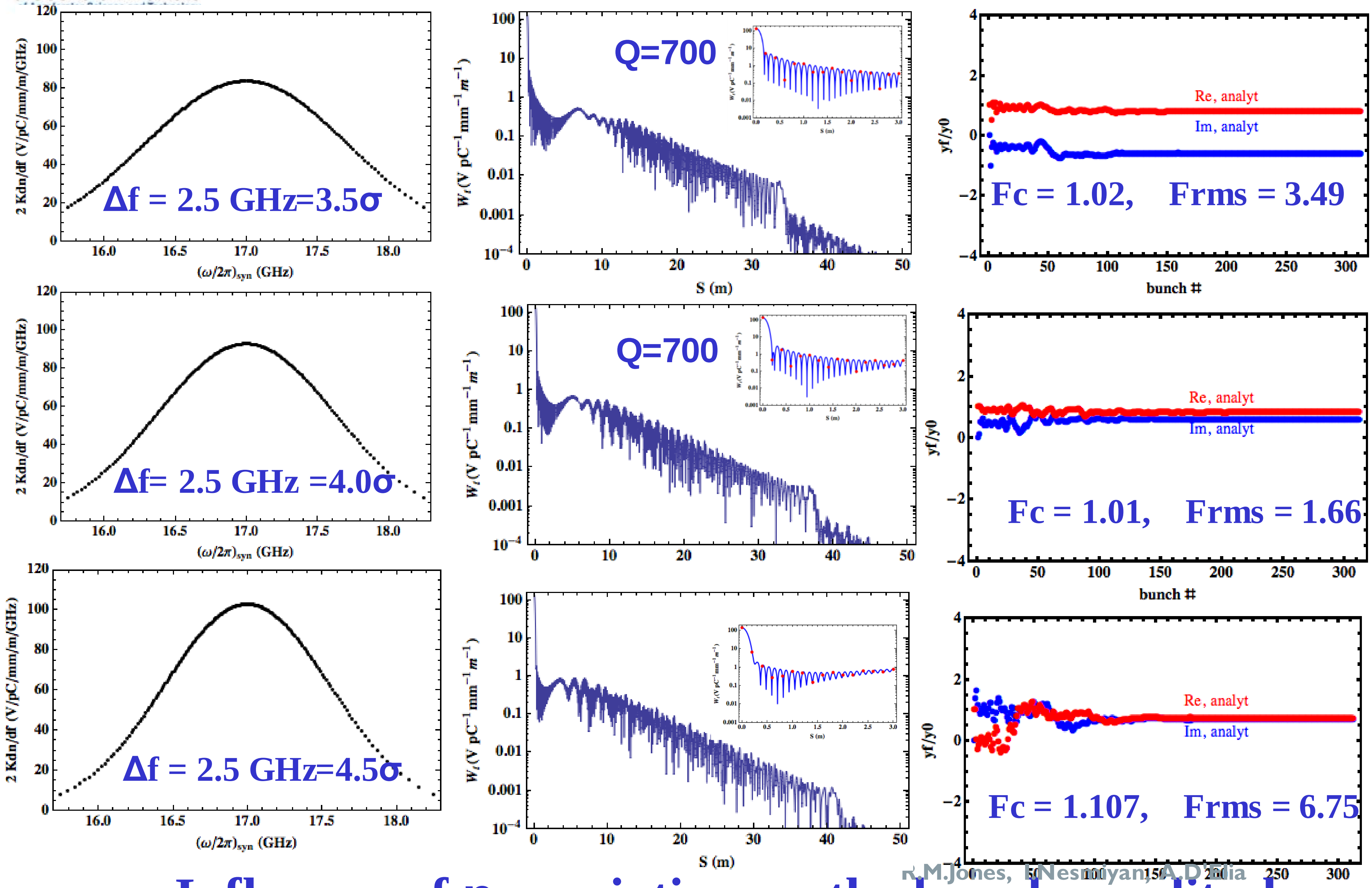




CERN and Uni. Manchester + C.I. collaboration

Structure	Wake (with phase information)		
	F_c	F_{rms}	F_w
DDS_A	1.29 x 10^{24}	1.25 x 10^{27}	1.32 x 10^{28}
8 x DDS_A	3.4 x 10^{5}	2.8 x 10^{7}	7.5 x 10^{8}
8 x DDS (Circular cells)	6573	5 x 10^{6}	1.55 x 10^{8}

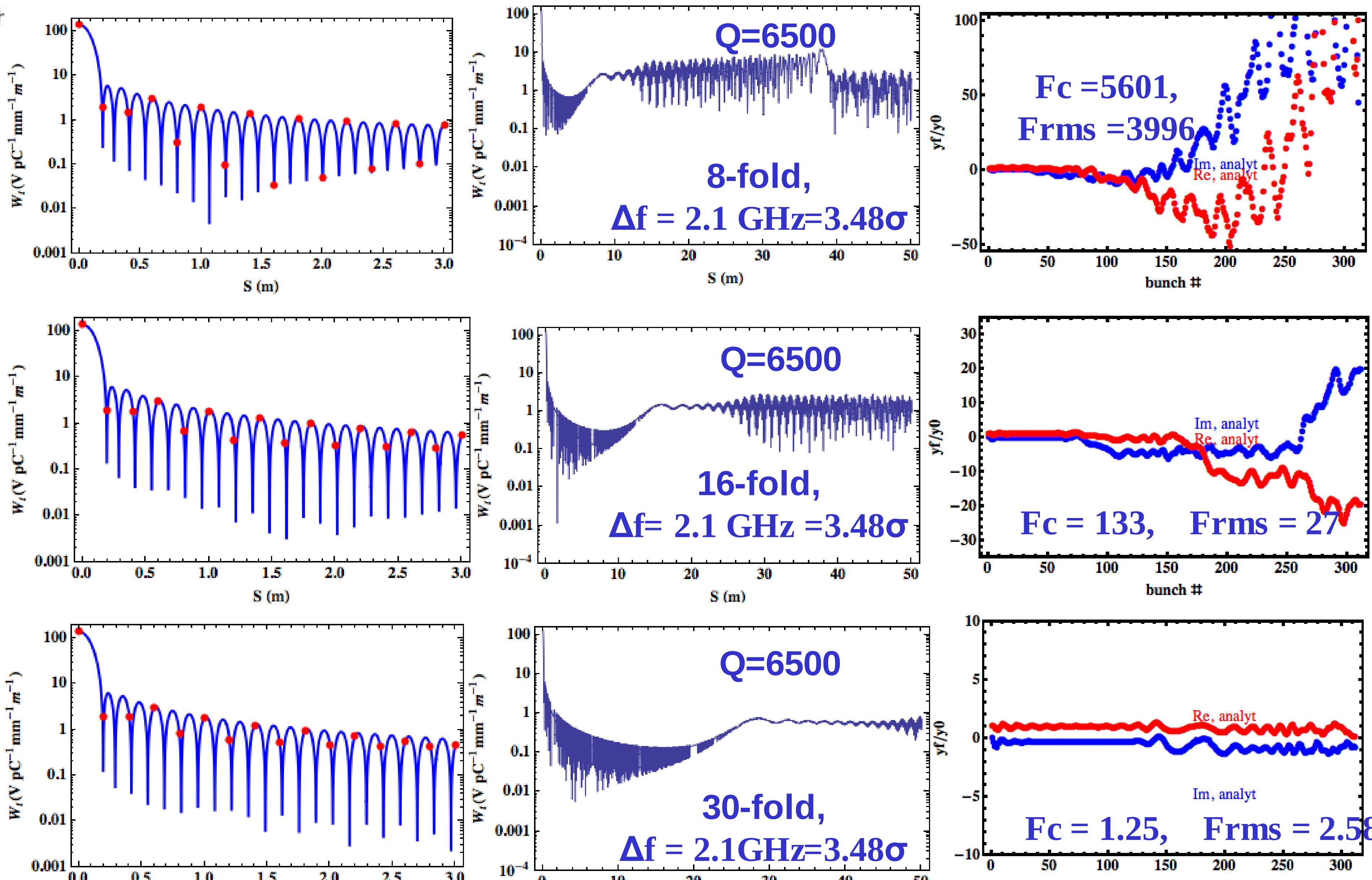
Beam Dynamics –Uncoupled Wake



R.M.Jones, I.Nesmiyan, A.D'Elia

Influence of η_σ variation on the bunch amplitude

Beam Dynamics

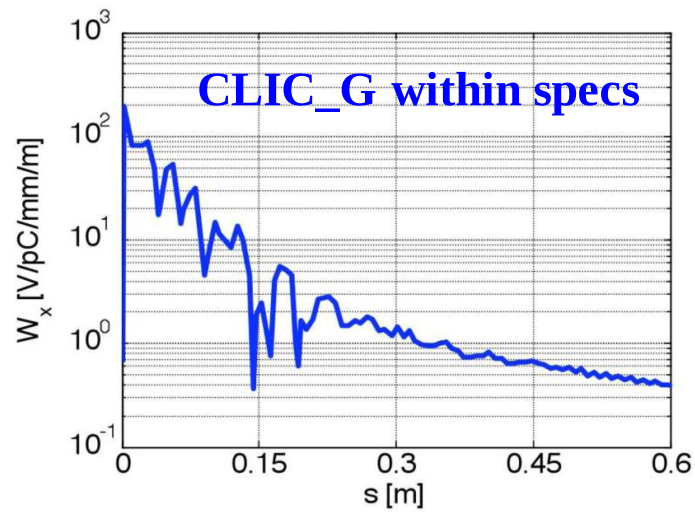


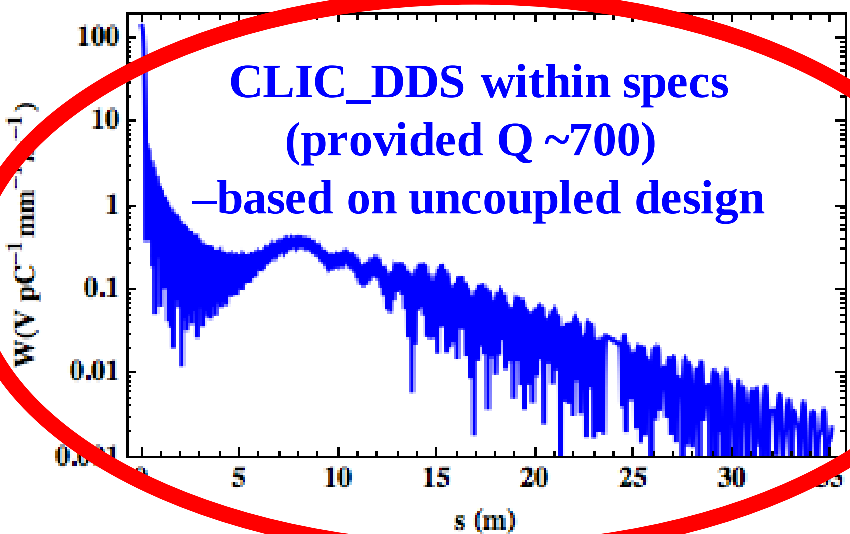
Pure Detuned Structures –no Manifold Damping!

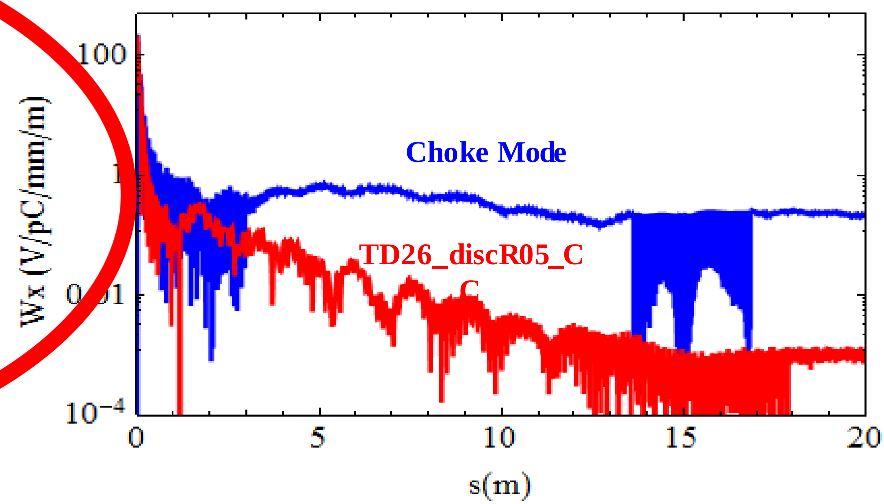
R.M. Jones, I.Nesmiyan, A.D'Elia

Beam Dynamics Summary

Design	F_c	F_{rms}
CLIC_G	1.01	4
CLIC_Choke	80	14
DDS x8 (Q~2000)	$3x10^4$	$2x10^6$
DDSx8 (Q=700)	1.03	1.5



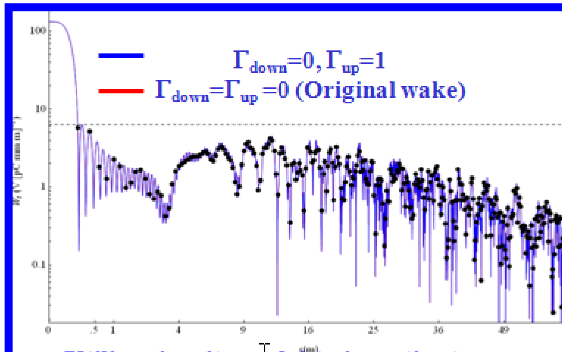




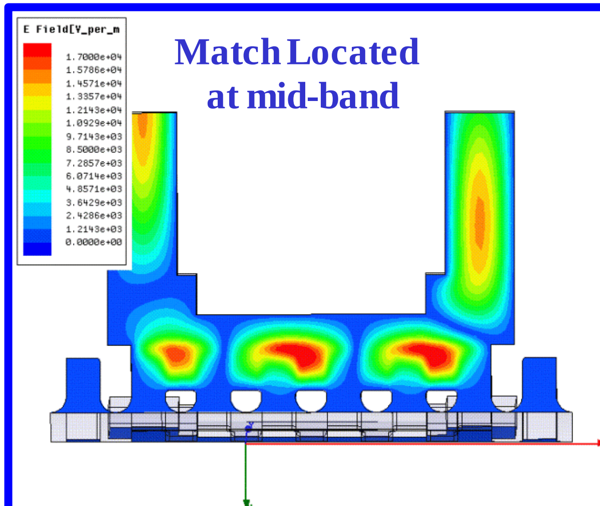
C.f. NLC/JLC design achieved Q≈500, with 4 -fold interleaving (SLAC-PUB- 9868)

Future Structure: CLIC_DDS_B

- Aim is to install in CTF3
- This structure will be based on a revised version of CLIC_DDS_A - equipped with HOM couplers and a compact coupler for fundamental mode
- Both wakefield suppression and high power performance will be tested
- Circuit model used to assess influence of HOM couplers on wakefields
- GdfidL simulations in progress – sans HOM coupler



- Utilise circuit model to investigate influence of removing HOM coupler
- Removal of upstream and retain downstream –indicates no appreciable difference in overall wakefield
- Removal of downstream impacts wakefield significantly.



Final Remarks

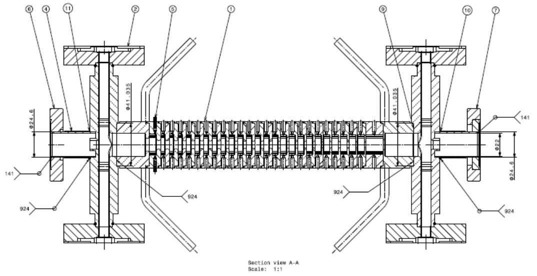
- ❑ **CLIC_DDS_A**
- **Full rf and mechanical design for structure equipped with mode-launcher couplers (based on 8-fold interleaving with full wakefield damping)**
- **Fabrication of cells expected to be complete at end of Feb 2012 (modified to June?) –and high power tested in 2012**
- **High power measurement at CERN/KEK in 2012?**
- **ASSET measurement of structures at SLAC in 2012?**
- **GdfidL and circuit model used to simulate structure**
- ❑ **CLIC_DDS_B**
- **Modification of regular cell design –beam dynamics study and enhanced damping profile under investigation**
- **Design of HOM and FP couplers for the new structure – progress (but a modified distribution needed to satisfied beam dynamics constraints)**
- ❑ **Additional Research Ongoing**
- **Increased damping (additional manifolds), hybrid (between heavy damping and manifold damped) structures –initial encouraging results but further work needed.**

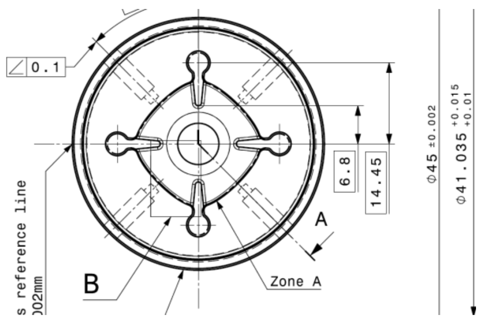
Acknowledgements

➢ 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

CLIC DDS Selected Peer Rev. 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.**
10. **R.M. Jones, NIMA, 2011.**
11. **V.F. Khan *et. al*, NIMA, 2011.**
12. **V.F. Khan, PhD thesis, 2011. (V.F. Khan, EuCARD Editorial Series of Monographs on Accelerator Science and Technology, Vol. 09. 2011)**





Selected Workshops/Confs*

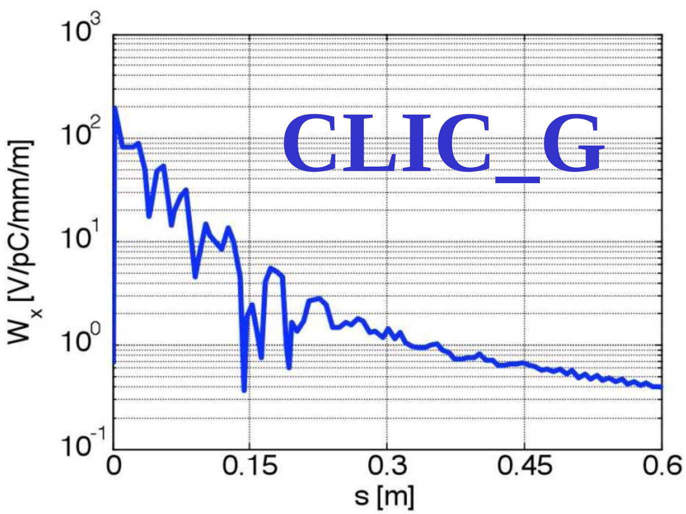
- R. M. Jones, *CLIC DDS: Wakefield Suppression and Beam Dynamics,* invited talk at the International Workshop on Breakdown Science and High Gradient Technology, KEK, April, 2012.
- R. M. Jones, *X-Band Linacs for CLIC (DDS), Light Source, and Medical Applications,* Talk given at the CI Business Partnerships Group, Cockcroft Institute, Feb 2012.
- R.M. Jones, *Baseline Physics and Design of DDS,* invited talk at DDS Day, January 2012.
- *Electrodynamics and Wakefields Studies at the University of Manchester*, invited talk at the Scientific Advisory Review, Cockcroft Institute, Dec. 2011.
- R.M. Jones, *Progress on the CLIC Manifold Damped and Detuned Accelerator,* invited talk at US Joint MAP & High Gradient RF Collaboration Workshop, LBL, November 2011.
- R.M. Jones, *High Gradient Linacs for the Next Generation of Linear Colliders*, invited talk on High Gradient Linacs for the Next Generation of Linear Colliders, Talk given at Faculty of Physics, Oxford University, July 2011.
- R.M. Jones, *Progress on the CLIC Manifold Damped and Detuned Accelerator*, invited talk at 5th Collaboration Meeting on X-band Accelerator Structure Design and Test Program, May 2011.
- R.M. Jones, *Wakefield Suppression in a Novel Detuned and Manifold Damped Linac*, invited talk given at Faculty of Physics, Yale University, April 2011.
- A. D'Elia, R.M. Jones, V.F. Khan, A. Grudiev, W. Wuensch, *Comparative Wakefield Analysis of a First Prototype of a DDS Structure for CLIC Main Linac*. Proceedings of the 2nd International Particle Accelerator Conference (IPAC11), Sept. 2011, San Sebastian, Spain.

*All conducted during April 2011 – April 2012

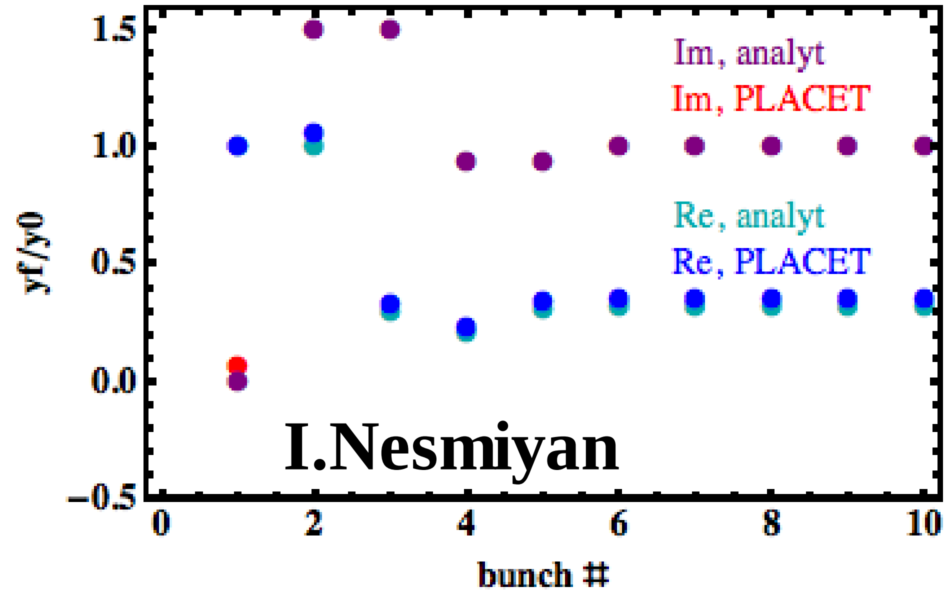
Supplementary Slides!

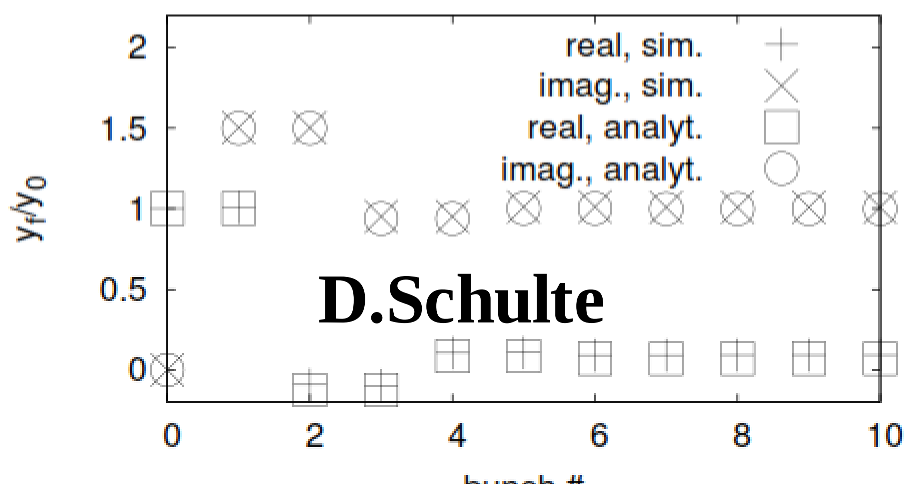
Beam Dynamics vs Analytical Model

Tools: D.Schulte's formalism, PLACET
(6.6kV/pC/m² first trailing bunch)

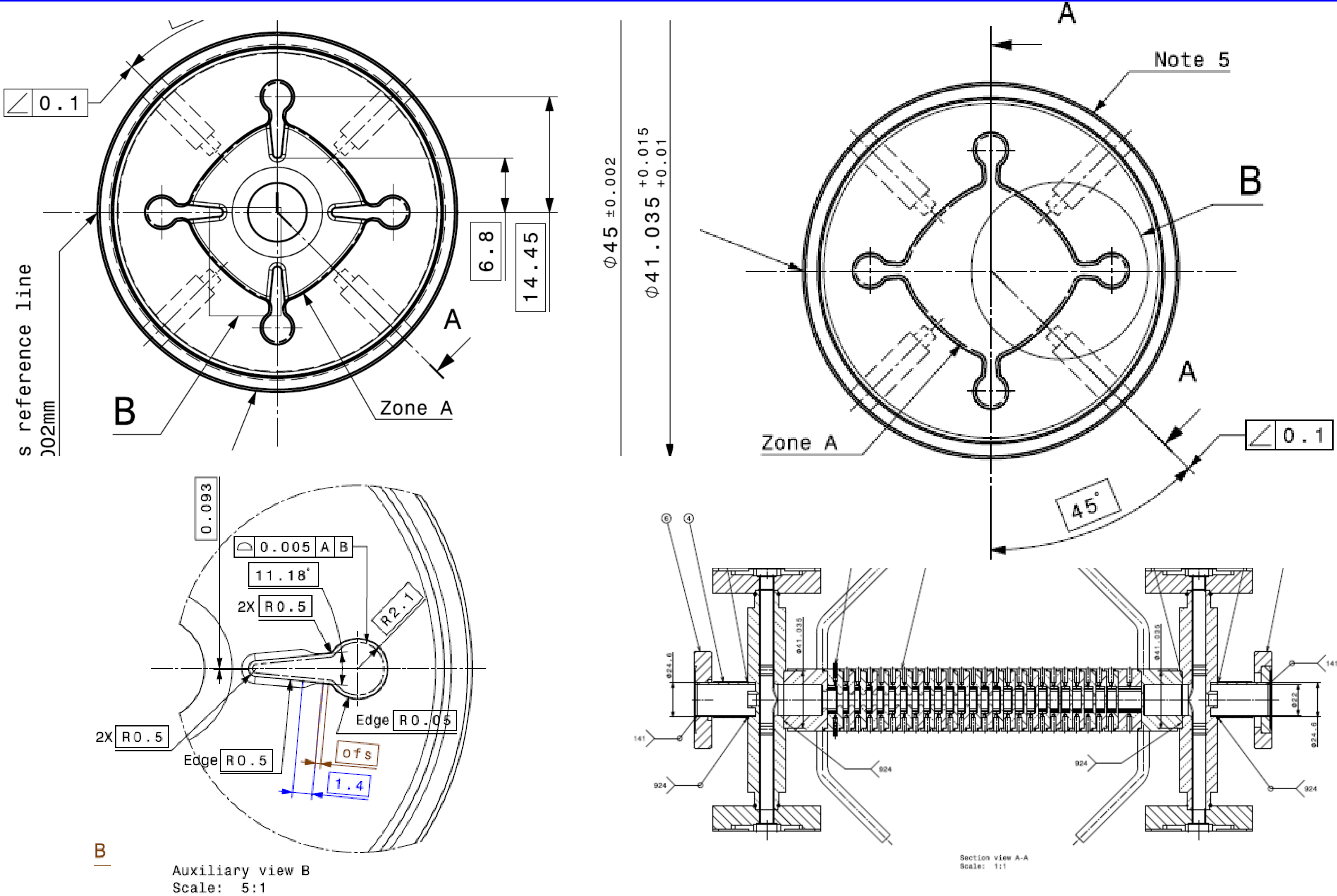


Fc =1.01, Frms = 4.86





CLIC_DDS_A Mechanical Eng. Design

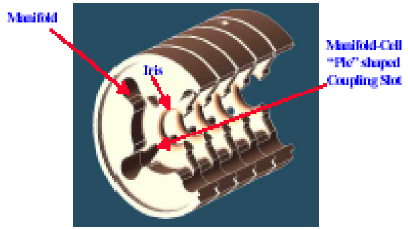


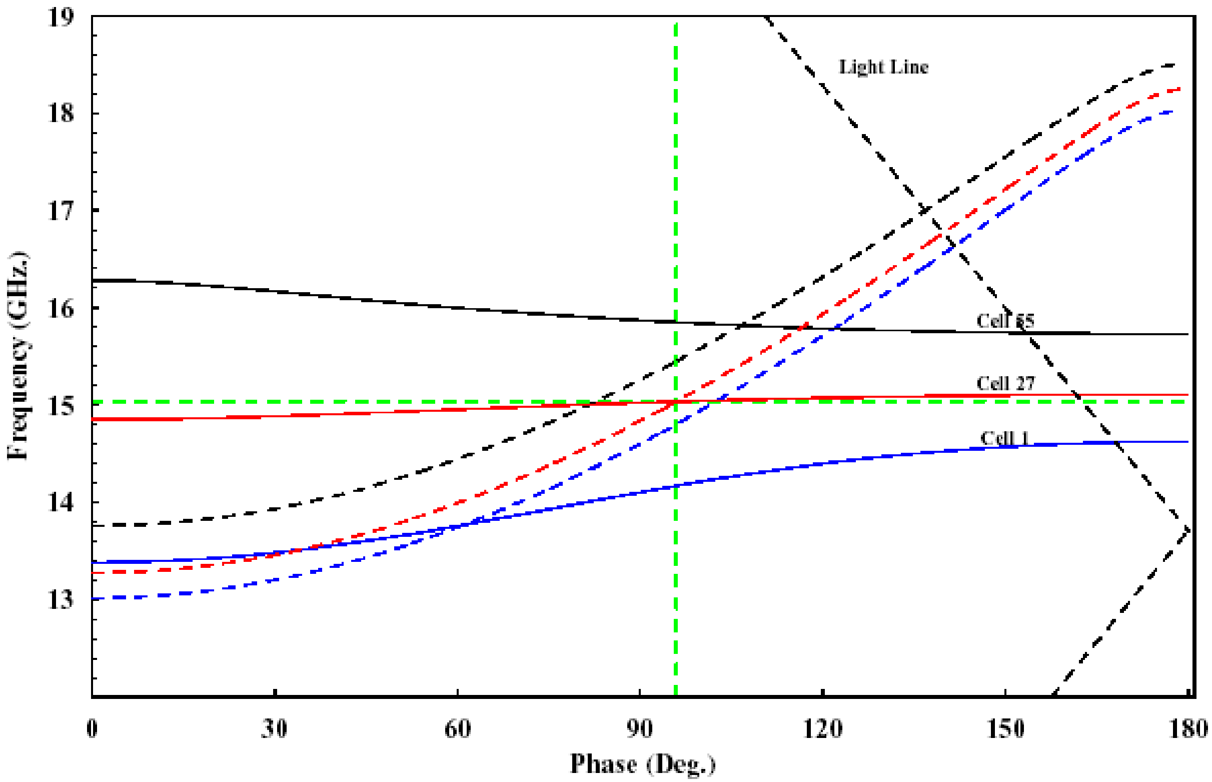
1. Physics of Manifold Mode Coupling to Dipole Modes

How Does Manifold Damping Work?

The fig. illustrates the dispersion curves from 3 cells of 55-cell accelerating DDS

* Strong coupling to the manifold occurs where dipole and manifold curves of the same color cross
*For mode 27 this occurs at ~15.03 GHz (green dashed line) at ~95.9 deg.
*Interpolation between the dipole curves shown at 0 and 180 suggests the mode is localized to cells: 20 to 34
*Also, from where the light line crosses 15.03 at ~162.6 deg.: the mode is excited at cell 20





2.4 Cell Qualification of CLIC_DDS_A