Progress on Damped and Detuned Accelerating Structures

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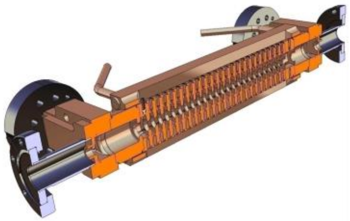
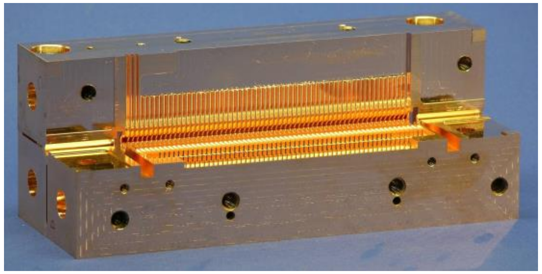
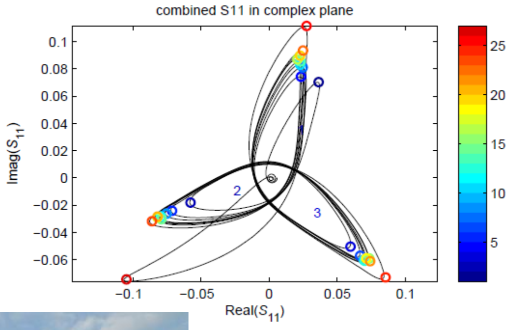
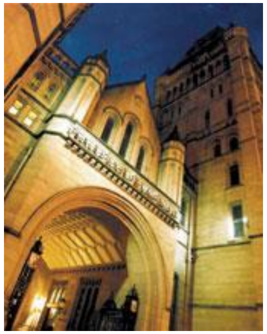








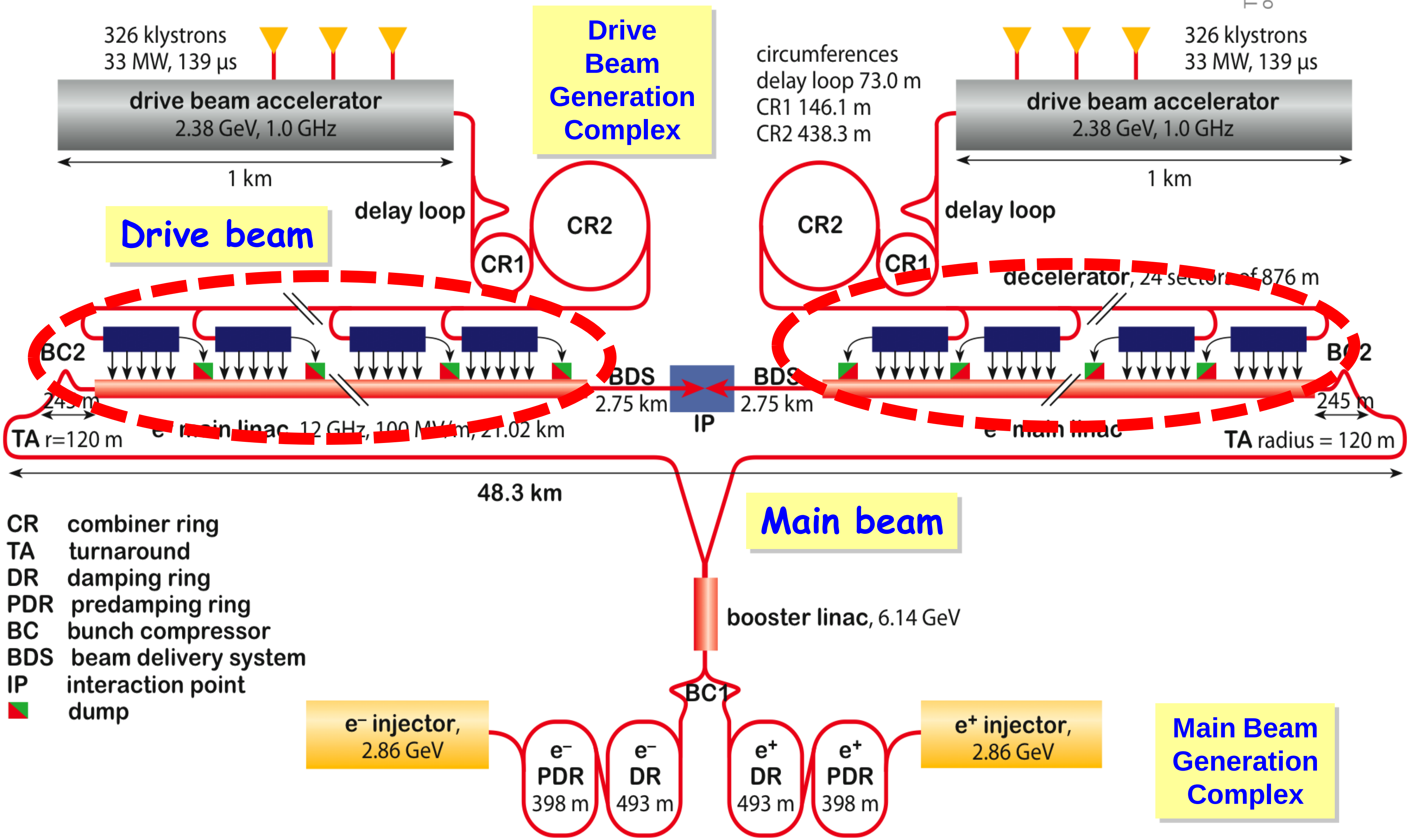
https://indico.cern.ch/event/353446/

Overview of WP 12.3.1

I. **Introduction to LCs and High Gradient Acceleration:**
   Self-induced wakefields & breakdown on cavity surface due e.m. fields

II. **Baseline CLIC design and alternate linac structures:**
   Heavy damped (CLIC_G), Choke suppression, Damped and Detuned (DDS)

I. CLIC –Overall Layout -3 TeV

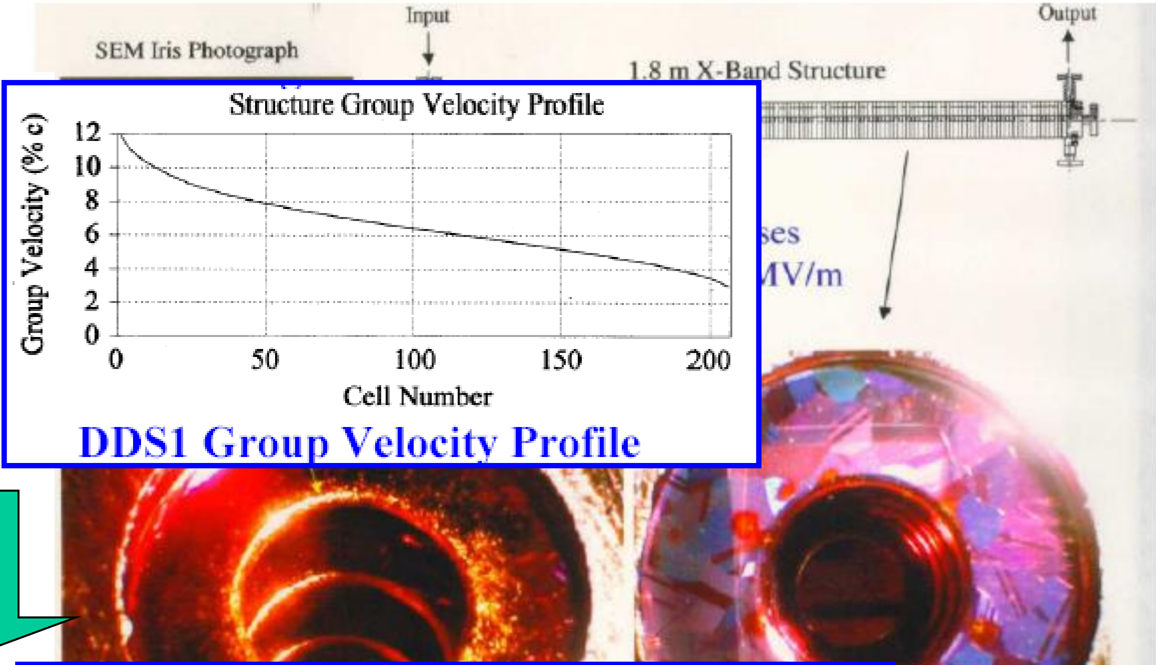


CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

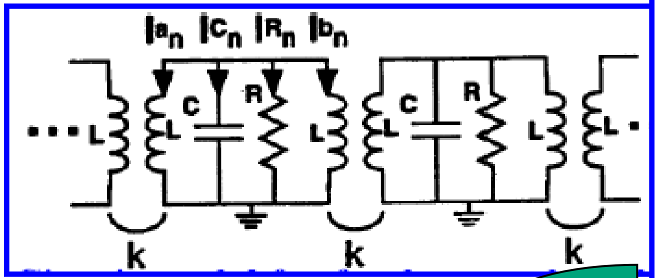
I. Effect of Breakdown Observed in Damped Detuned Structures (DDS)

- Input end indicated worst damage
- Prompted a major programme to investigate means to mitigate for this

1. Shorter structures
2. Lower group velocity (v_g)
3. Standing wave (SW) structures



DDS1 Group Velocity Profile



Circuit model of power absorbed in breakdown

$$P_{abs} \simeq \frac{R_A}{(R/Q)^2} \frac{v_g^2}{\omega/c} \frac{4\sin\phi\,(\text{grad})^2}{\phi\sin\phi + 2v_g\cos\phi}$$

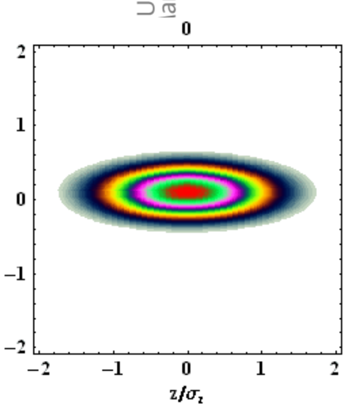
R_A resistance of breakdown, v_g is the group velocity, ϕ is the synchronous phase advance ($=2\pi/3$ for DDS1), grad the accelerating gradient, and R and Q are the shunt impedance and quality factor evaluated at the synchronous phase

I. Rationale for Wakefield Suppression

- Charged particle beam excites parasitic modes
- Why damp these modes?
- Here we discuss linear collider applications & developing light source applications - in which a train of bunches is accelerated
- In order to maintain Beam Quality and to ensure BBU (Beam Break Up) resonant instabilities do not occur the modes with particularly large ‘kick factors’ must be damped

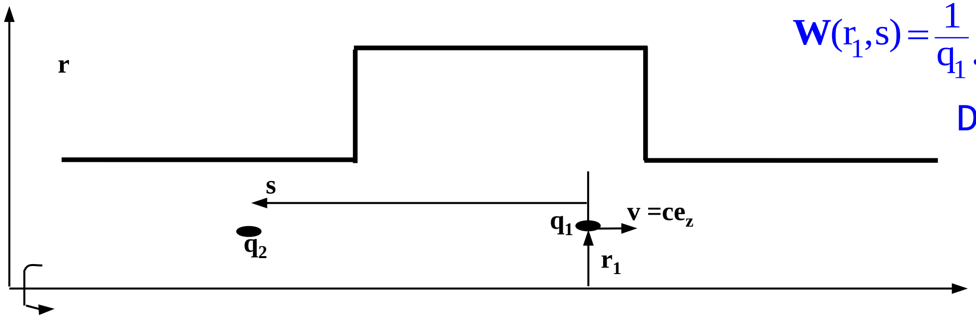
I. Features of Wakefields

- **Short-range wakefields ~ $a^{-3.8}$: sets a lower limit on aperture: a ~ 0.17λ**
- **Long-range wakefields: disrupt the trailing bunches (2820 in the present ILC design), dilute the beam emittance and can give rise to an instability known as BBU (Beam Break Up)**
- **The driving bunch excites an EM field in the cavity which persists long after the original bunch has left the cavity.**
- **The transverse force exerted on the trailing particles has a complicated dependence on position within the structure. However, the integral along the axis of the transverse force (F_t) is much simpler and this defines W(s), the wakefield:**



Contours indicate density of original Gaussian distrn.

BBU Due to Short-Range Wakefields

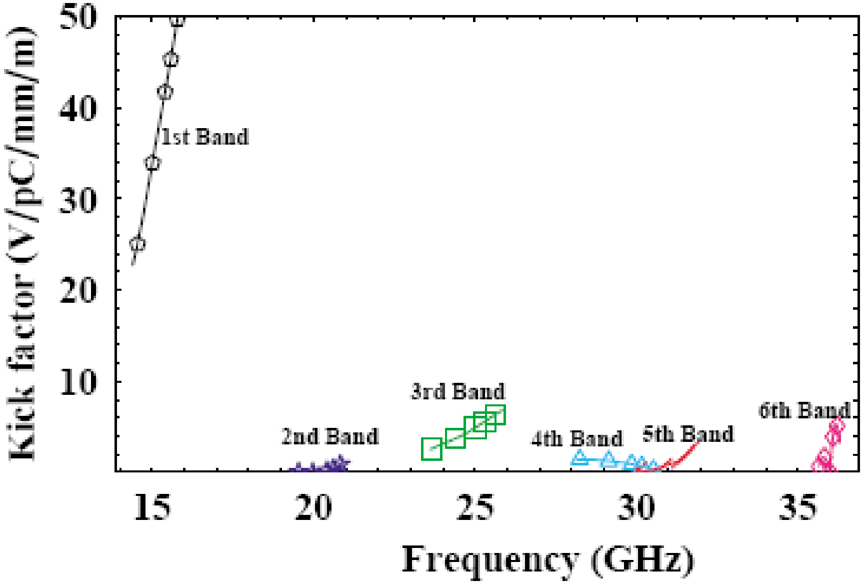


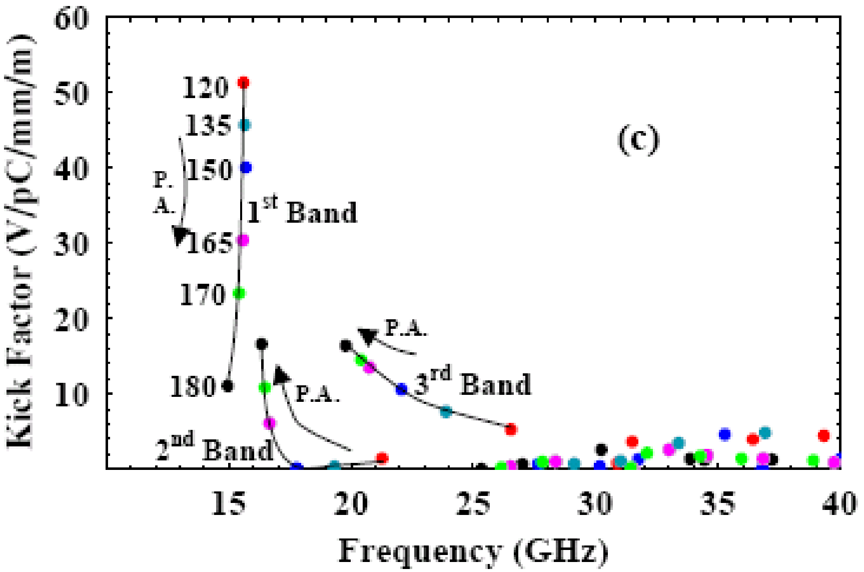
$$\mathbf{W}(r_1,s)=\frac{1}{q_1}\int_{-\infty}^{\infty}dz\left[\mathbf{E}(r_1,z,t)+c\mathbf{e}_z x\mathbf{B}(r_1,z,t)\right]_{t=(s+z)/c}$$

$$\mathbf{Dp}=q_1q_2\mathbf{W}(s)r_1/c$$

- **Long range wakes are suppressed by careful detuning and damping.**

I. Band Partitioning



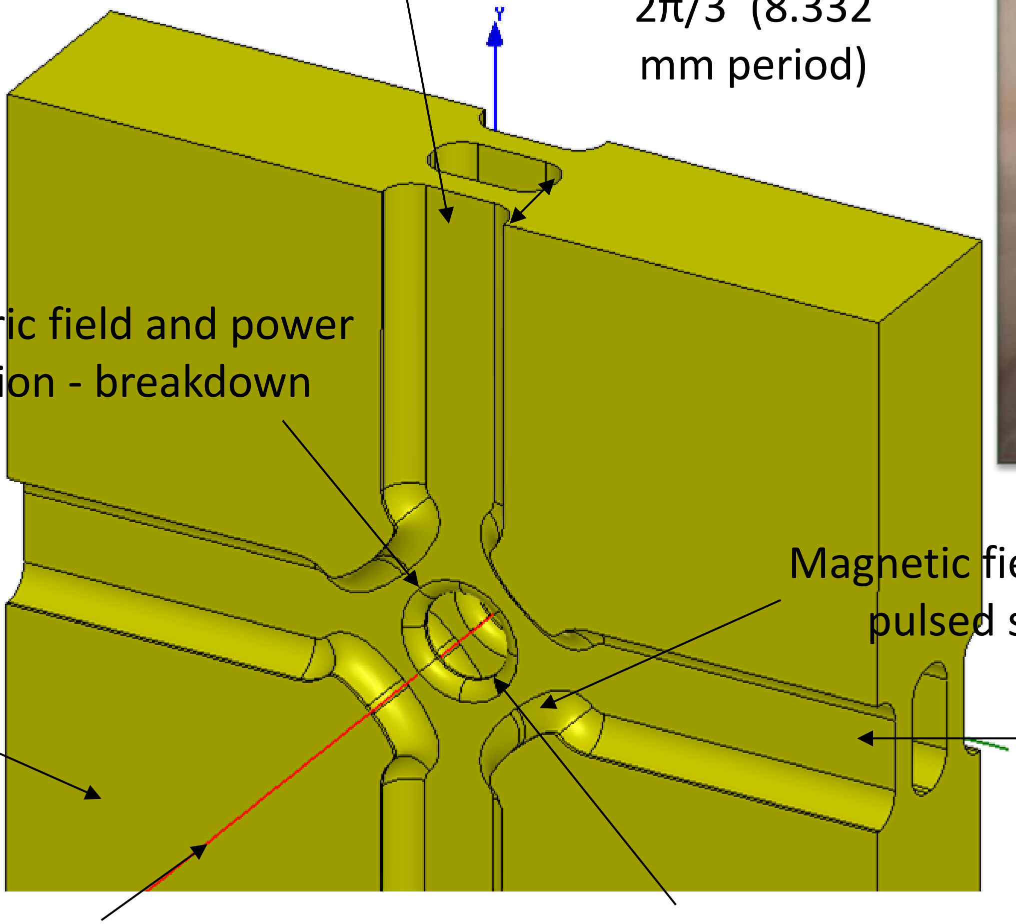


- ➢ Band partitioning of kick factors in 206 cell DDS1 X-band structure (f_{acc}=11.424 GHz). Largest kick factors located in the first band. Third and sixth bands although, an order of magnitude smaller, must also be be detuned along with the 1st band.
- ➢ CLIC design f_{acc} =11.9942 GHz shifts the dipole bands up in frequency.

- ➢ The partitioning of bands changes with phase advance. Choosing a phase advance close to π per cell results in a diminution of the kick factor of the first band and and enhancement of the 2nd and 3rd bands. A similar effect occurs close to π/2.
- ➢ Kick factors versus phase advance for cells with an iris radius of ~ 4.23 mm.

Ref: Jones et. al, 2003, SLAC-PUB 9467

II. CLIC Baseline Accelerating Structure



HOM damping waveguides

11.9942 GHz, $2\pi/3$ (8.332 mm period)

Alignment

High electric field and power flow region - breakdown

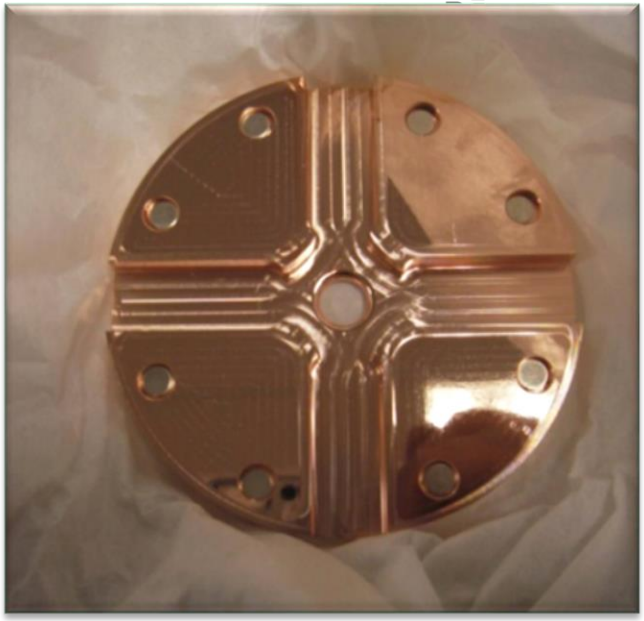
Magnetic field concentration – pulsed surface heating

Cooling

Vacuum pumping

Beam and rf

Short range wakefields



Heavy Damping, Q~10. Dielectric materials impinge into structure

W. Wuensch, CERN

II. 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 have an impact on breakdown (Jiaru Shi leads this)

- **Viable alternative is presented by University of Manchester's CLIC_DDS design - parallels the DDS developed for the J/NLC (Japanese/Next Linear Collider), and entails:**

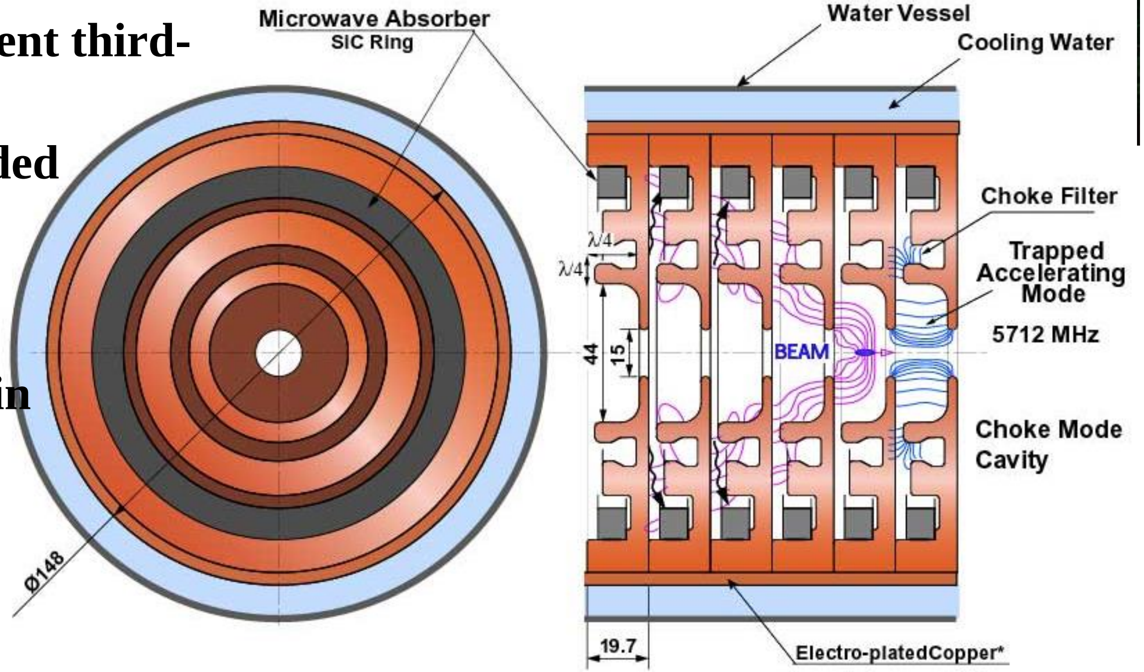
1. **Detuning the dipole bands by forcing the cell parameters to have a precise spread in the frequencies –presently Gaussian Kdn/df- and interleaving frequencies of adjacent structures.**
2. **Moderate damping Q ~ 500-1000**

II. C-Band Choke Mode HOM Suppression

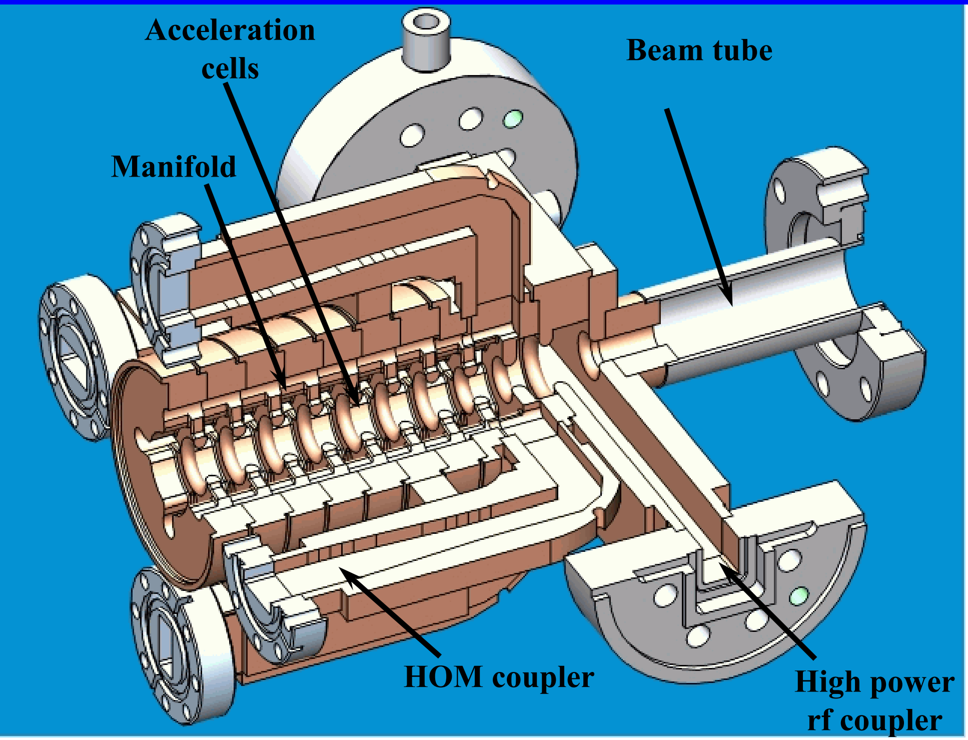
SPring-8 (Super Photon ring-8 GeV)

- Synchrotron radiation facility, including compact SASE Source in Japan
- High peak-brilliance soft X-ray FEL project for R&D A
- Angstrom X-ray laser facility.
- SCSS (SPring-8 Compact SASE Source)will provide six order of magnitude peak-brilliance enhancement compared to the current third-generation sources at 3 ~ 20 nm
- C-Band (5.712 GHz) linacs provided with choke mode damping
- HOMs flow out through radial channels
- Fundamental mode trapped within the structure ($\lambda/4$)
- 35-40 MeV/m

Ref: 1. R. M. Jones, *Wake field Suppression in High Gradient Linacs for Lepton Linear Colliders*, Phys. Rev. ST Accel. Beams 104801, 2009.
2. http://www-xfel.spring8.or.jp
3. T. Shintake, Japanese J.Appl.Phys.31:L1567-L1570 (1992)

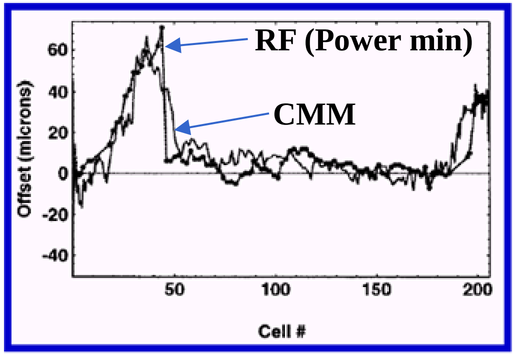


II. Features of CLIC DDS Linac

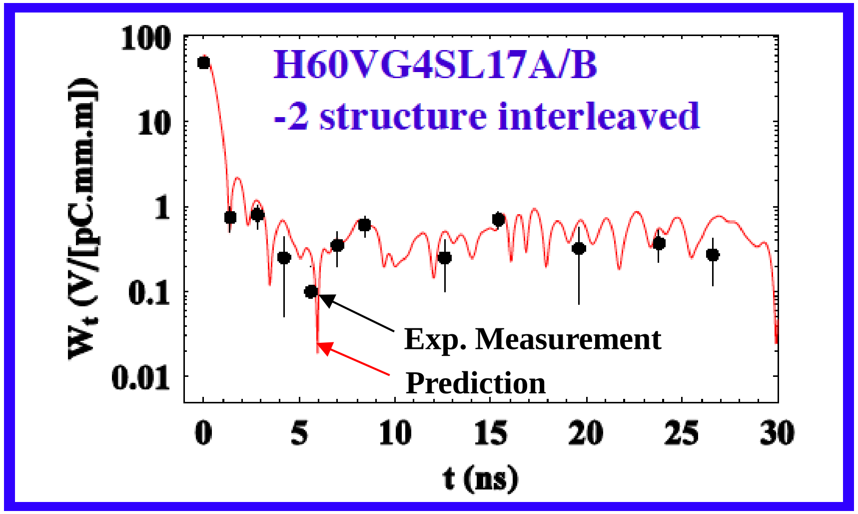


- NLC/GLC SLAC/KEK RDDS structure (left) illustrates the essential features of the conceptual design
- Each of the cells is tapered –iris reduces (with an erf-like distribution –although not unique)
- HOM manifold running alongside main structure removes dipole radiation and damps at remote location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

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

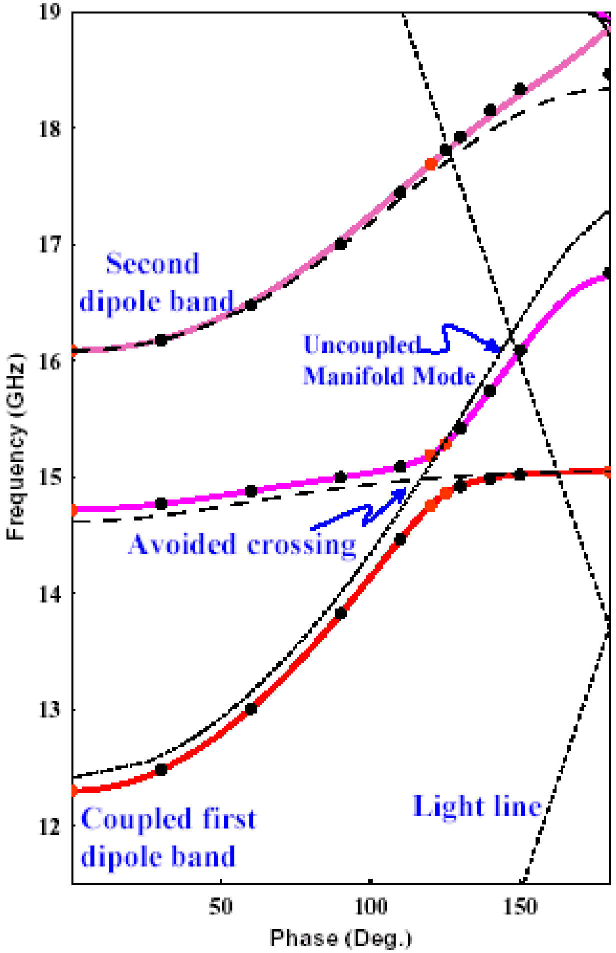


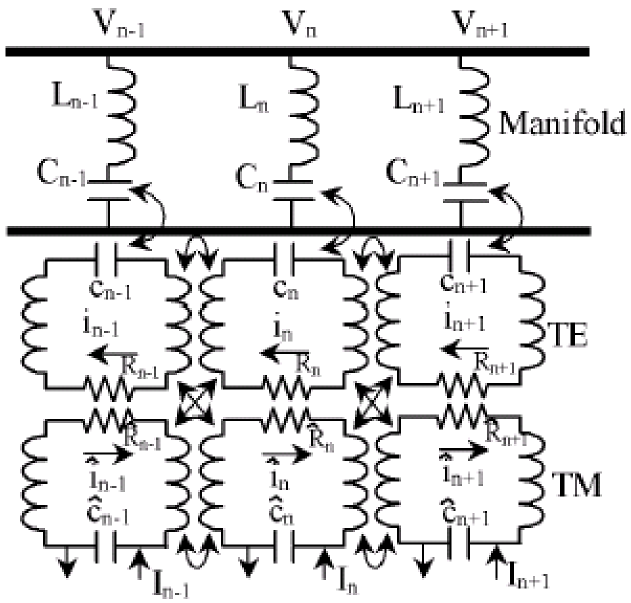
Remote Cell Alignment Diagnostic



Wake Suppression

II. Prediction Based on Circuit Model of DDS

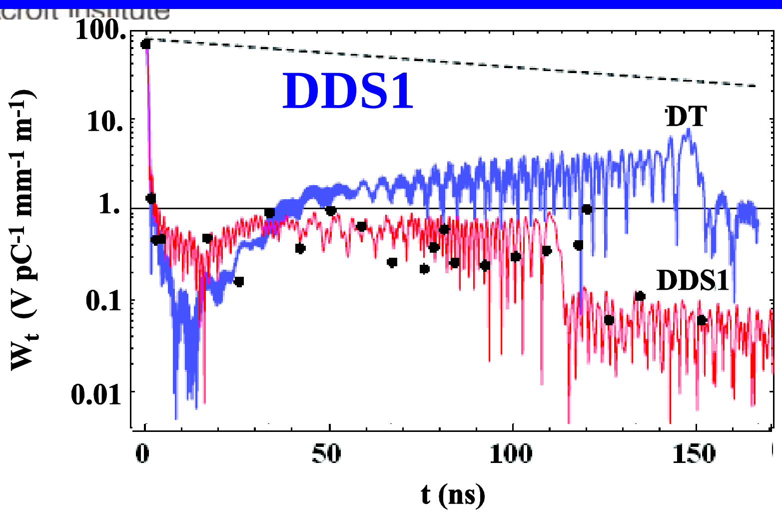


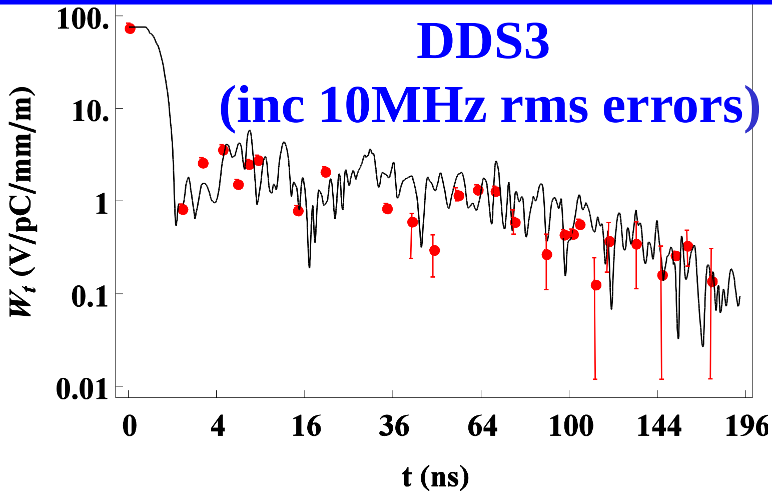


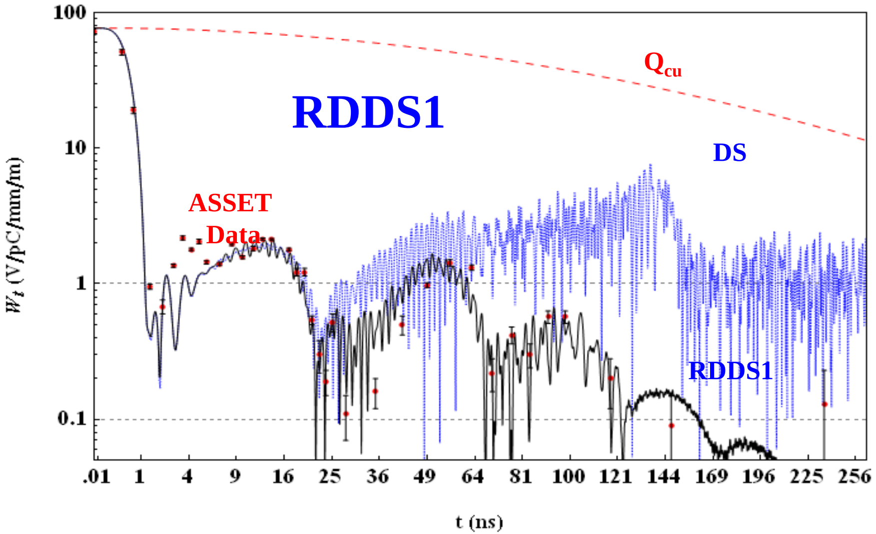
Three cells in the chain are illustrated. TM modes couple to the beam . Both TM and TE modes and excited and the coupling to the manifold is via TE modes. The manifold is modeled as a transmission line periodically loaded with L-C elements.

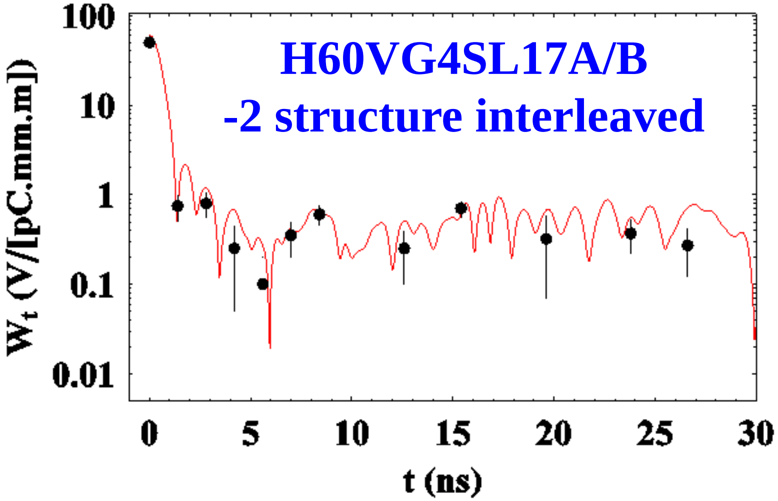
****Wakefield damping in a pair of X-band accelerators for linear colliders.R.M. Jones , et al, Phys.Rev.ST Accel.Beams 9:102001,2006.**

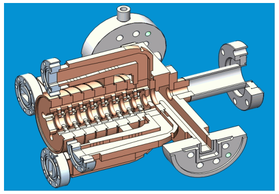
II. Summary of GLC/NLC Exp vs Cct Model











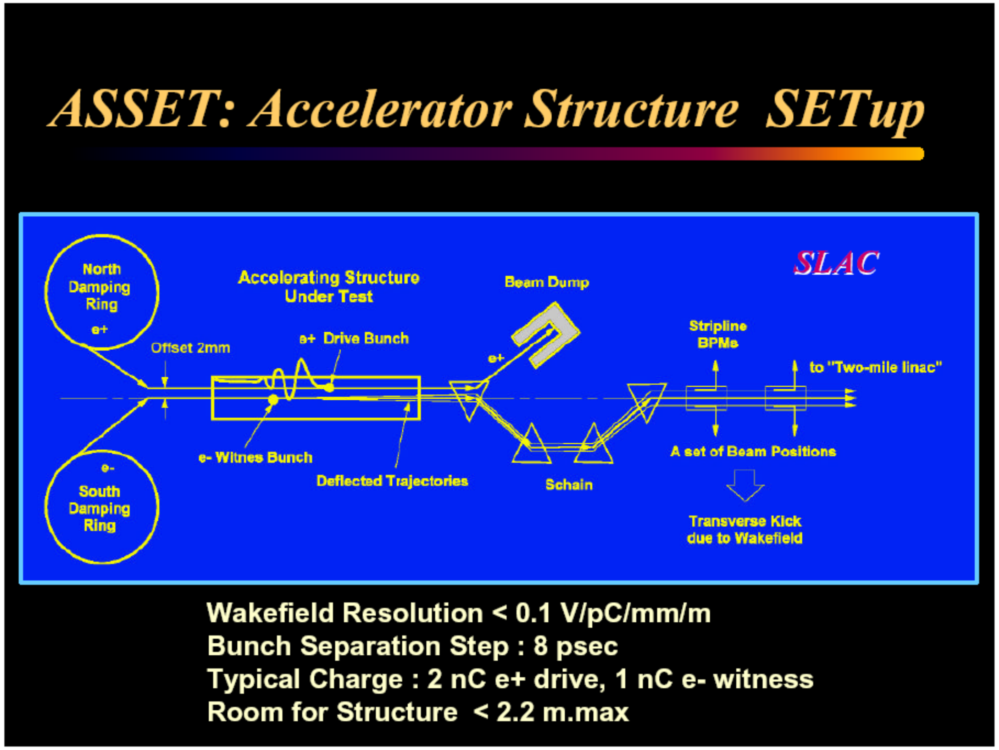
Conspectus of GLC/NLC Wake Function Prediction and Exp. Measurement (ASSET dots)

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.

II. Measurement of Wakefields/HOMs



ASSET: Accelerator Structure SETup

Wakefield Resolution < 0.1 V/pC/mm/m
Bunch Separation Step : 8 psec
Typical Charge : 2 nC e+ drive, 1 nC e- witness
Room for Structure < 2.2 m.max

- **$W_\perp$ is the transverse wake function at time t behind the drive bunch, E_w (~ 1.2 GeV) is the witness bunch energy and Δy_d is the offset in the drive bunch from the electrical centre of the accelerating structure.**
- **Wake function units are transverse voltage per drive charge (en_d), drive offset and structure length (L_s), and $\zeta = e^2 L_s n_d \exp(-\omega^2\sigma^2/c^2)$**

- **Electron bunch serves as the witness bunch**
- **In traversing the DUT, the witness bunch is deflected by the wake function generated by the positron drive bunch.**
- **Witness bunch passes though chicane and down linac where trajectory is recorded by BPMs**
- **The transverse wake function is determined by measuring the change in the witness bunch deflection per unit change in the drive bunch offset in the structure.**

- **Angular kick imparted to the witness bunch is found from ratio of the transverse to longitudinal energy:** $\boxed{\Delta\theta_y = \zeta W_\perp(t)\Delta y_d / E_w}$

Ref: R. M. Jones, *Wake field Suppression in High Gradient Linacs for Lepton Linear Colliders*, Phys. Rev. ST Accel. Beams 12, 104801, 2009

II. CLIC Design Constraints

1) RF breakdown constraint

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

2) Pulsed surface temperature heating

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

3) Breakdown Factor

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

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

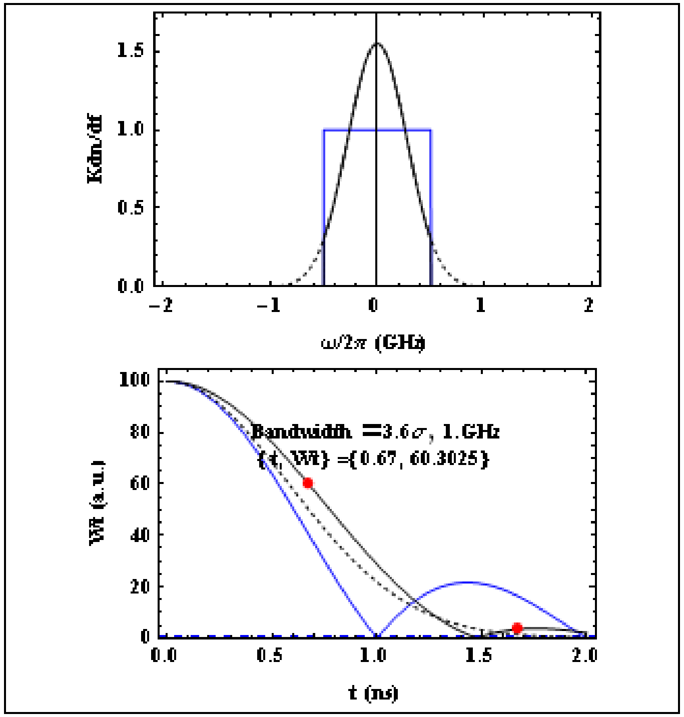
$$W_{t1} \le \frac{6.667\times 4\times 10^{9}}{N}\,(V/[pC.mm.m])$$

Wake experienced by successive bunches must also be below this criterion

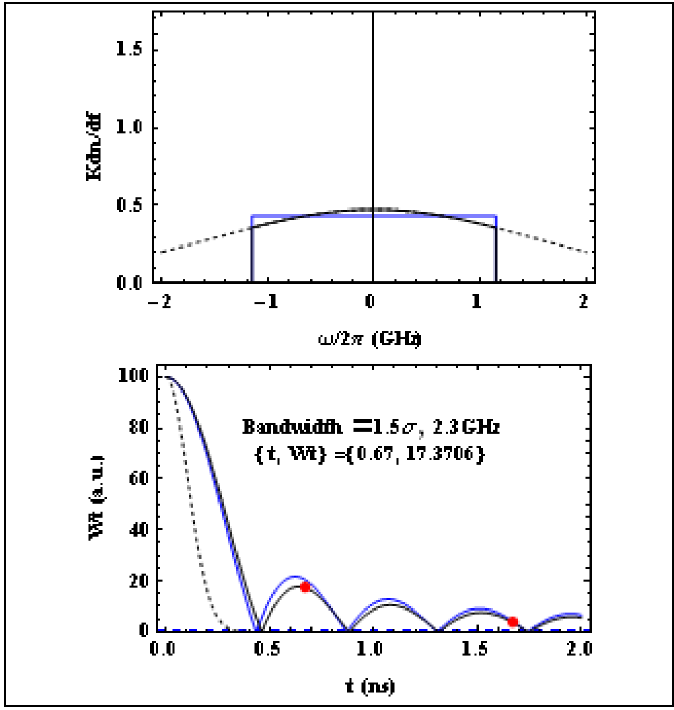
Ref: Grudiev and Wuensch, Design of an x-band accelerating structure for the CLIC main linacs, LINAC08

II. 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

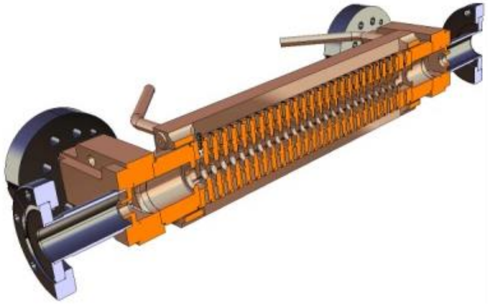


σ Variation

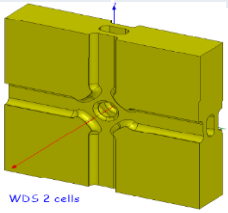
Truncated Gaussian :

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

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



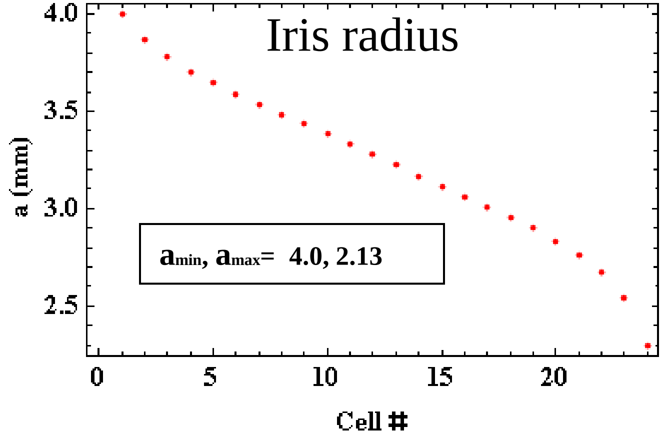
Lowest dipole
Δf ~ 1GHz
Q~ 10

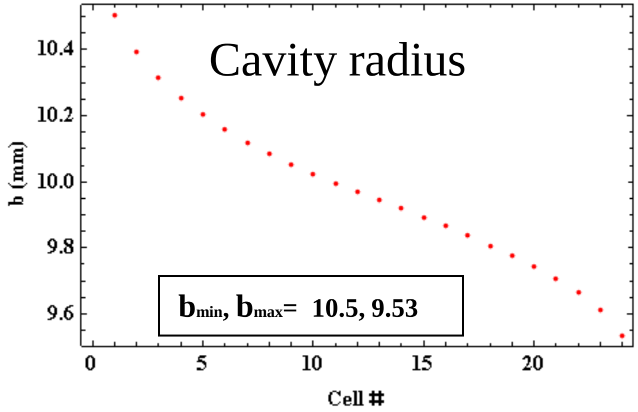


CLIC_G

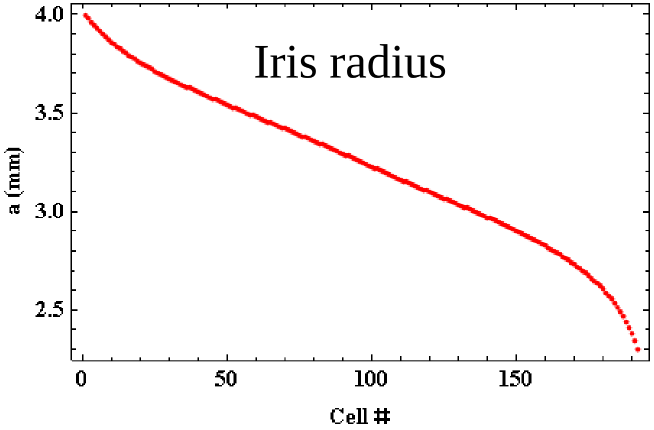
=> CLIC_DDS Uncoupled Design

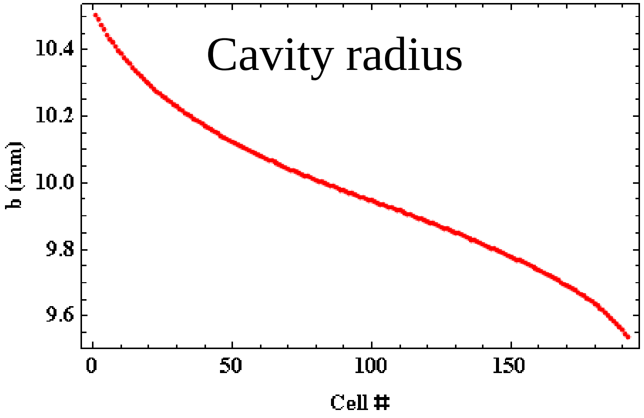
II. Structure Geometry: Cell Parameters



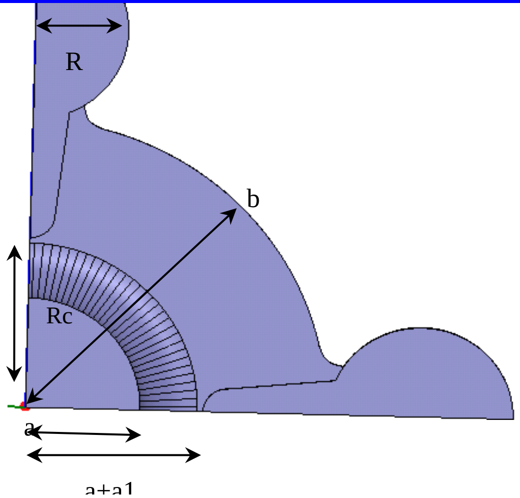


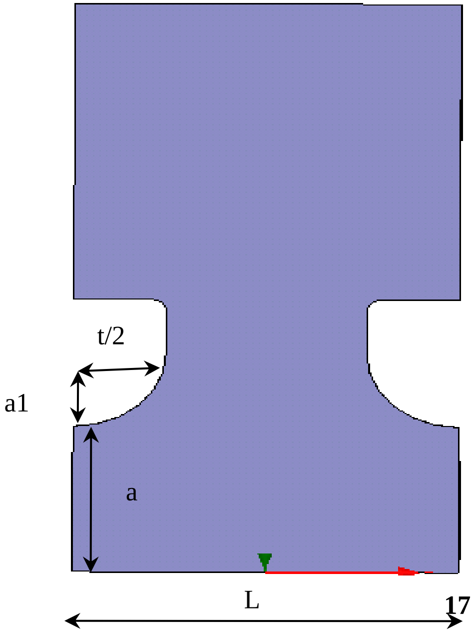
Sparse Sampled HPT
(High Power Test)





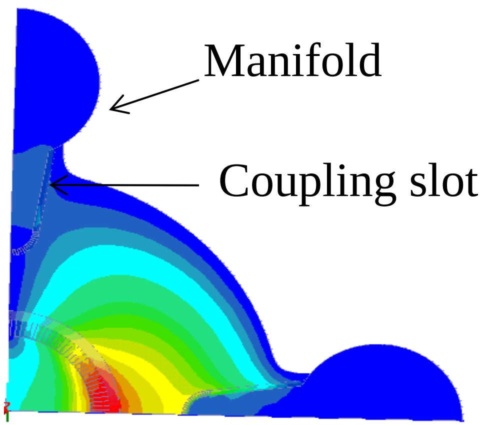
Fully Interleaved
8-structures



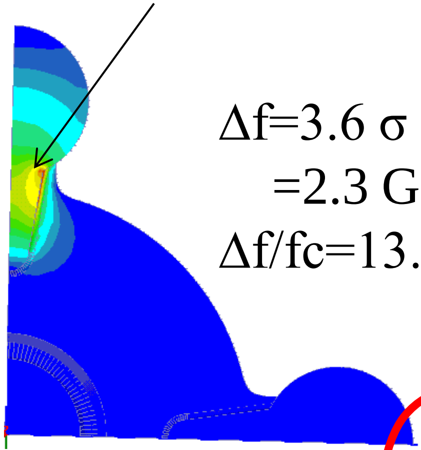


II. Summary of CLIC_DDS_C

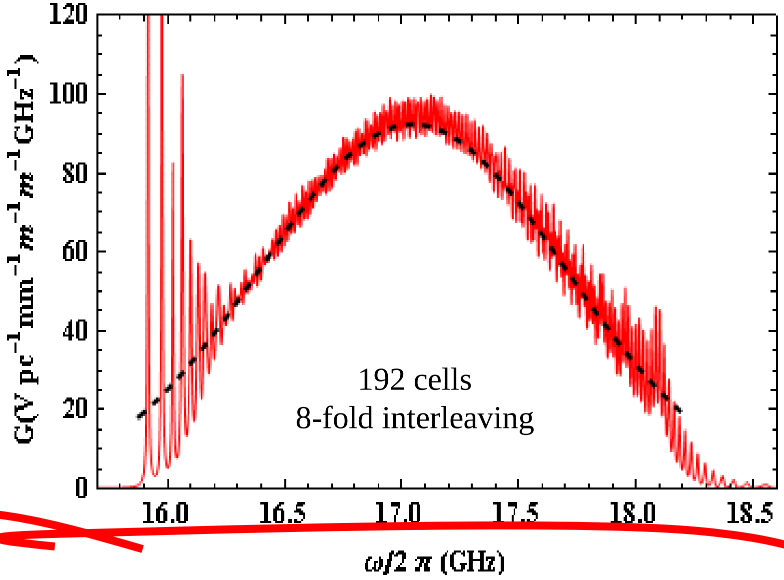
Dipole mode

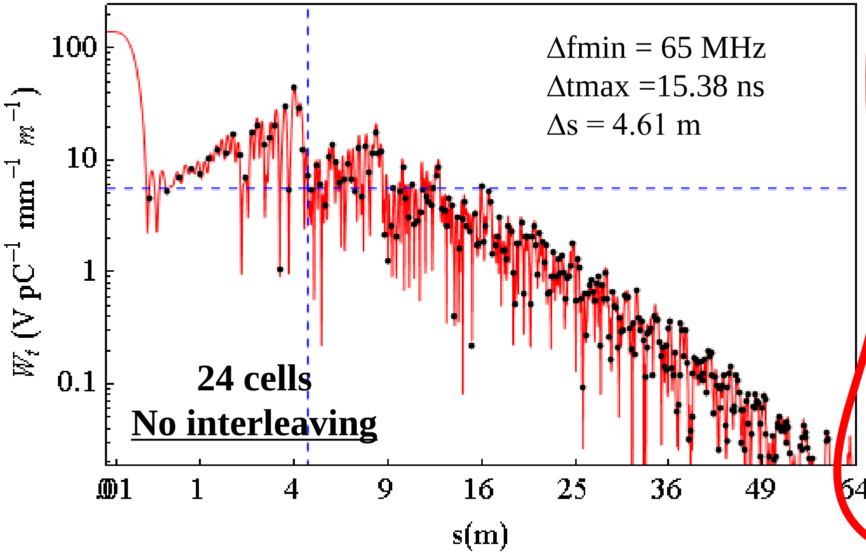


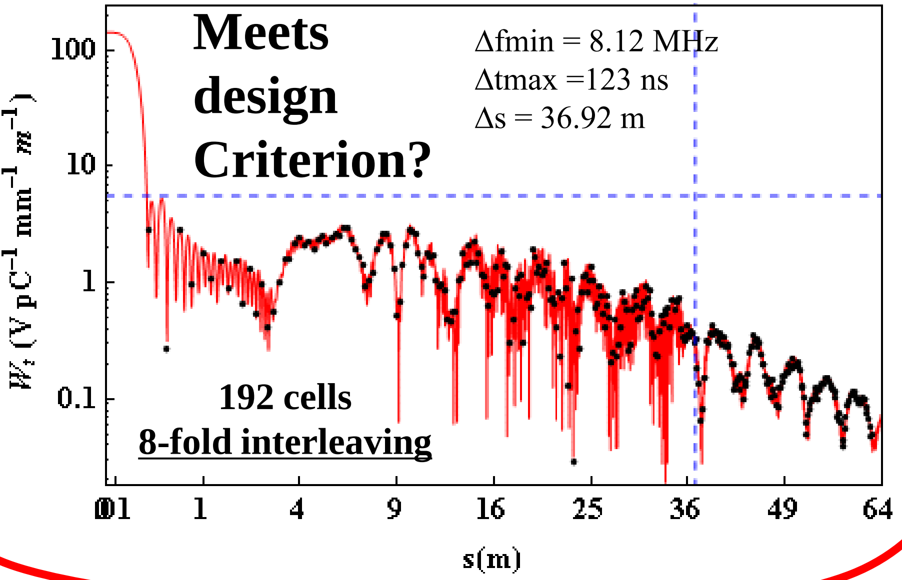
Manifold mode



Δf=3.6 σ
=2.3 GHz
Δf/fc=13.75%

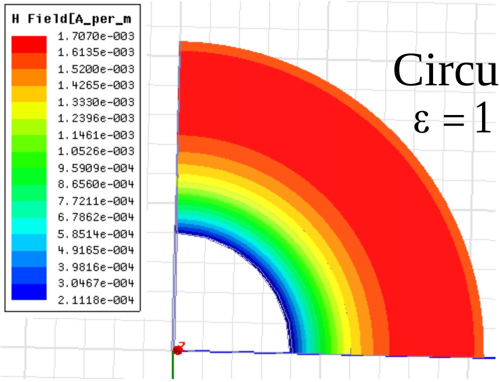




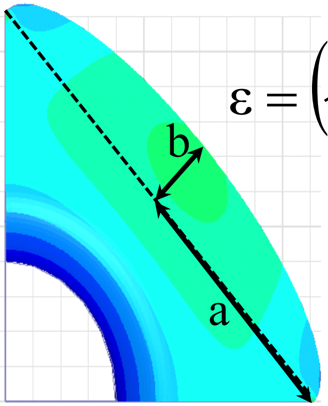


H CLIC_DDS_E Elliptical Design –E Fields

Single undamped cell
Iris radius=4.0 mm

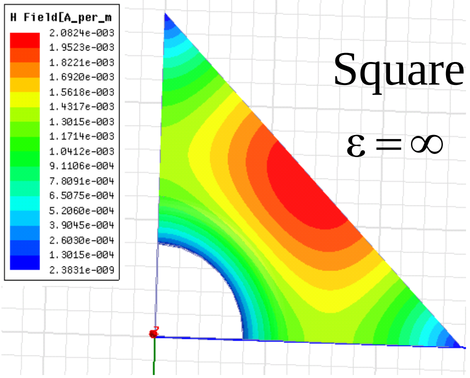


Circular
$\varepsilon = 1$

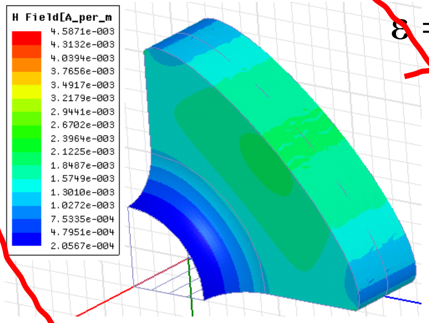


$$\varepsilon = \left(\sqrt{2} - 1\right)\frac{a}{b}$$

Convex ellipticity



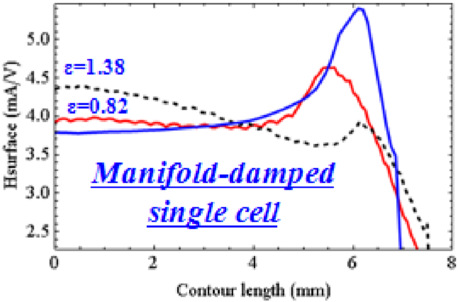
Square
$\varepsilon = \infty$



$\varepsilon = 1.38$

	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



Manifold-damped single cell

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

0 **Chosen design**

II. Beam Dynamics

Direct Effect

- **Assumes bunches are effected one- on-one –usual assumption for several 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 nearest neighbours***

Indirect Effect

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

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

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

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:

$$\boxed{y_f = \left(1 + a\right) y_i}$$

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

II. 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

$$\boxed{\begin{aligned} F_c &= \frac{1}{n}\sum_k \left|\sum_j A_{kj}\right|^2 \\ F_{rms} &= \frac{1}{n}\sum_{k=0}^{n-1}\sum_{j=1}^{k}\left|A_{j,k}\right|^2 \end{aligned}}$$

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

In the limit of an infinite number of bunches

$$\boxed{\begin{aligned} y_f &= A y_i \\ A &= \exp(a) \end{aligned}}$$

Returning to a finite number of bunches Taylor expand:

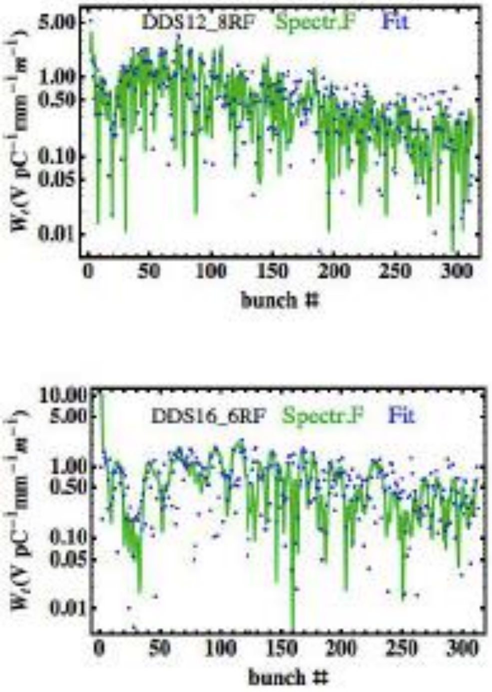
$$A = \sum_{k=0}^{\infty}\frac{a^k}{k!} = \sum_{k=0}^{n-1}\frac{a^k}{k!}$$

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

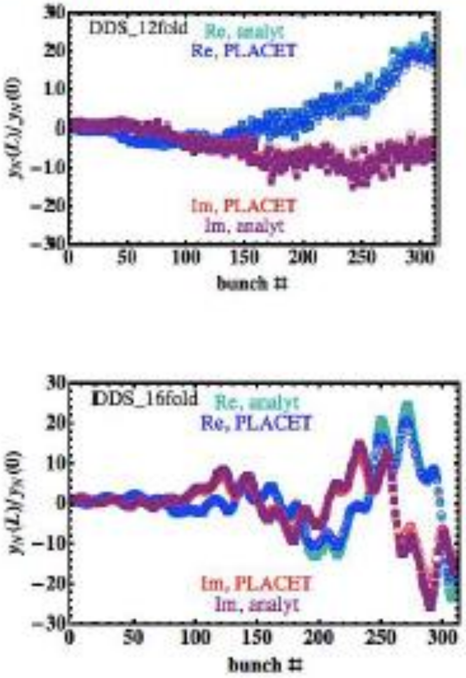
II. Tracking with Placet vs. Analytical

- Wakefield for -12 and 16 fold interleaving (corresponding to an equivalent structure of 288 and 384 cells, respectively) is shown.
- Point-like bunches are assumed in the calculation and tracking simulation.
- Random errors are excluded.
- It is evident that the analytical method predicts insufficient wakefield suppression.

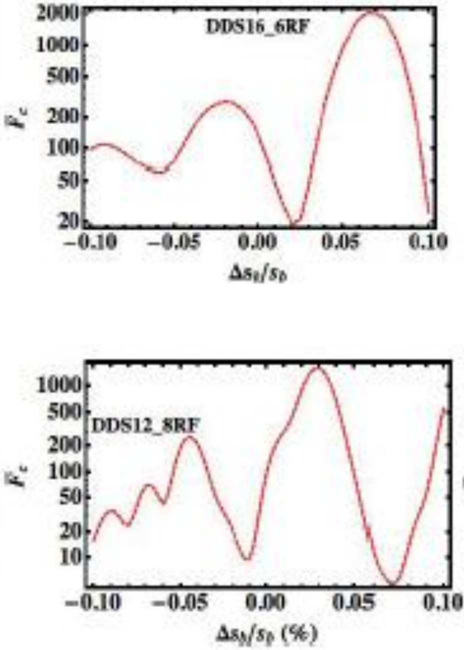
Absolute value of the amplitude wakefield



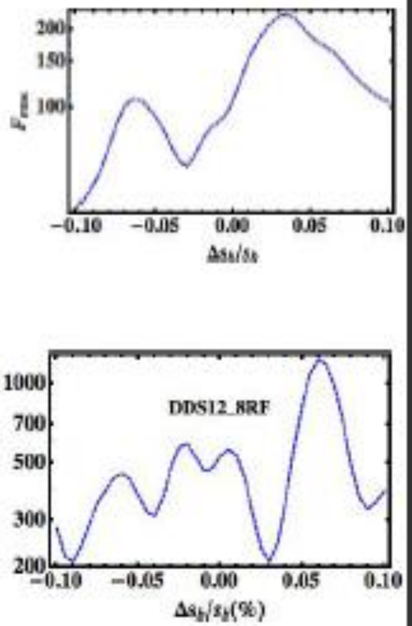
The normalized amplitudes of the bunches at the end of the CLIC main linac for an offset incoming train.



Coherent jitter – *Fc*



RMS of jitter – *Frms*



II. Tracking Simulations Inc. Realistic Bunch & Machine Parameters

- Previous simulations based on point-like bunches
- Here we explicitly include realistic bunch length, energy spread, random errors (expected to arise from fabrication of >71,000 structures)
- Also, systematic frequency errors are investigated by small changes in the bunch spacing
- Reduces emittance dilution significantly!

Selected beam parameters

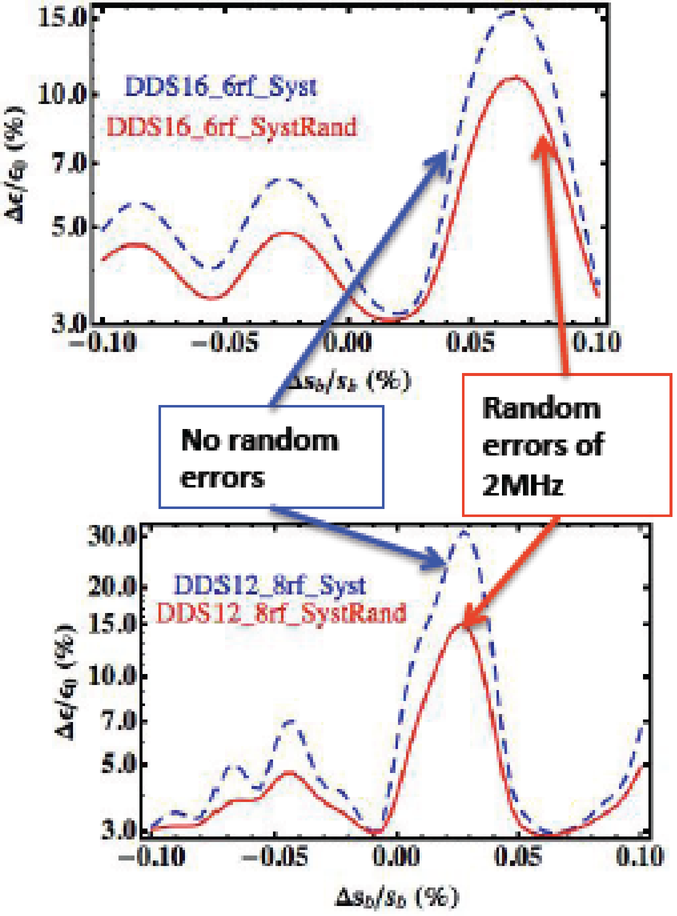
Parameter	Value	Parameter	Value
Initial beam energy, E_0	9 GeV	Bunch length, σ_z	44 μm
Final beam energy, E	1500 GeV	Initial $\gamma\epsilon_x$	550 nm
Particles per bunch	3.72×10^9 / 4.2×10^9	Final $\gamma\epsilon_x$	660 nm
Bunch spacing	0.15/0.2m(6/8 rf periods)	Initial $\gamma\epsilon_y$	10 nm
Bunch train length	156 ns	Final $\gamma\epsilon_y$	20 nm
Number of bunches	312	Initial σ_E/E	1.6%

II. Tracking Simulations Inc. Realistic Bunch & Machine Parameters

DDS16_6rf_3.72e9p/bunch

DDS12_8rf_4.2e9p/bunch

Emittance dilutions versus small changes in the bunch spacing (PLACET, realistic bunches)



No random errors

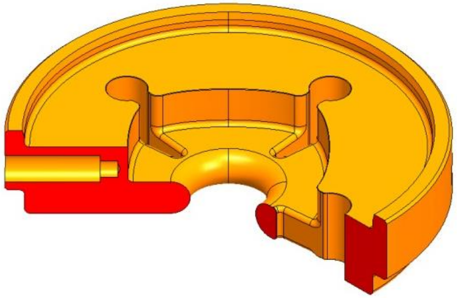
Random errors of 2MHz

- Perfect linacs
- Bunch train initially offset by σ_y (0.5 μm) , energy spread σ_E/E=1.6%

II. General Features of CLIC_DDS_A

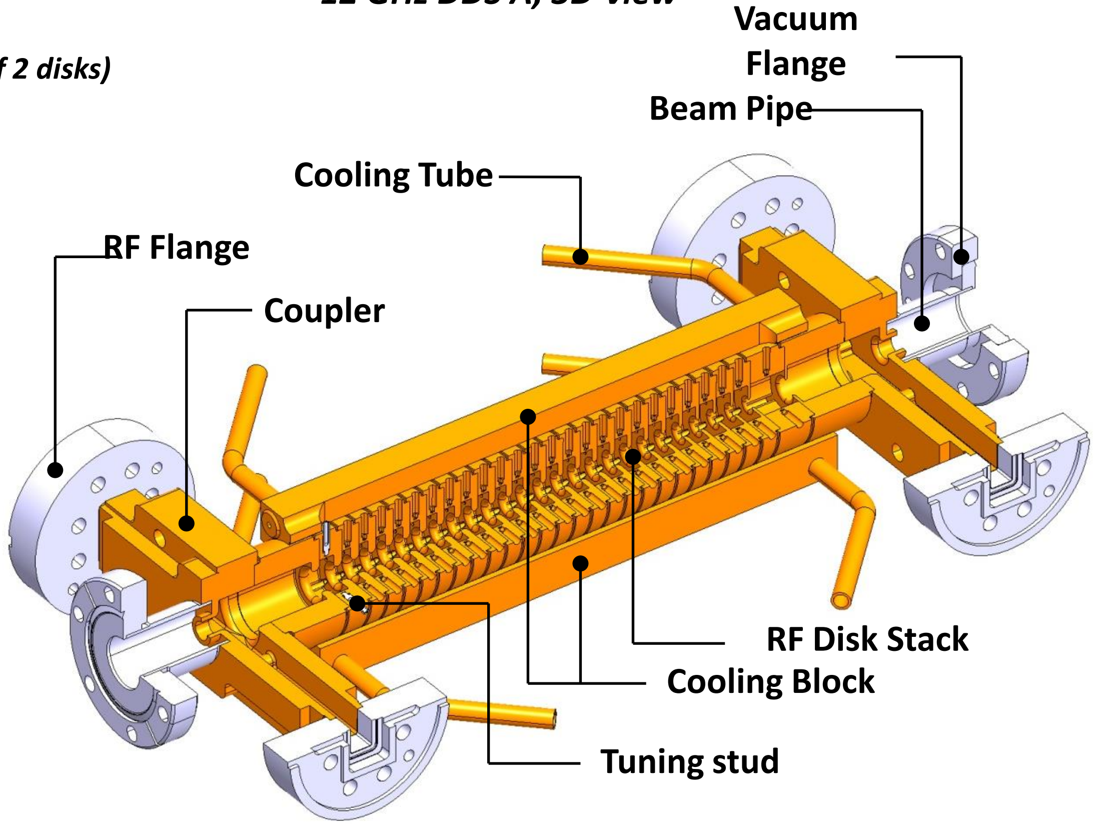
General design features

- **RF Disks stack**
  - **VDL**
    - ***24 regular cells***
    - *2 matching cells*
    - *Input and output cells*
  - **KEK**
    - ***24 regular cells***
    - *2 matching cells (comprised of 3 disks)*
    - *Input and output cells (each comprised of 2 disks)*
- **Mode Launcher couplers (VDL and KEK)**
- **"Push-Pull" tuning system (VDL and KEK)**
  - ***4 tuning studs brazed inside each RF disk***
- **Cooling system (VDL and KEK)**
  - *2 parallel cooling circuits*
  - *2 twin cooling blocks*



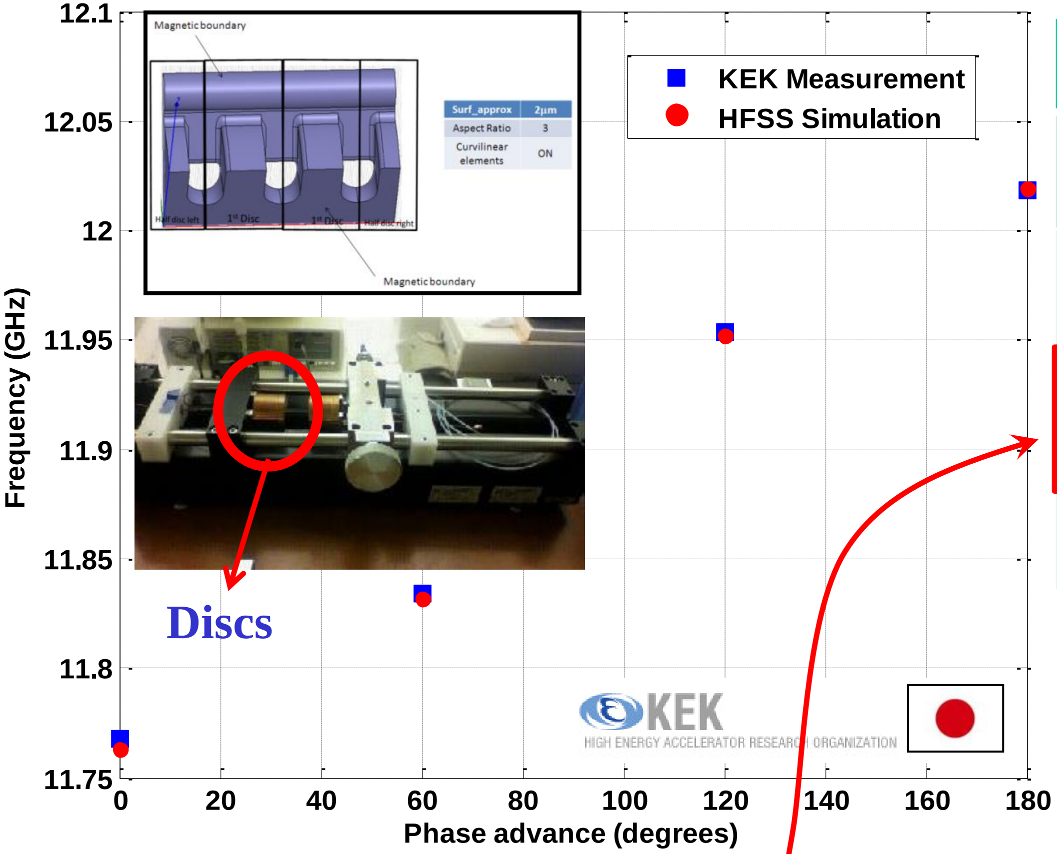
Regular RF disk. Three-quarter view

12 GHz DDS A, 3D-view



Courtesy G. Riddone, V. Soldatov

First Comparison Between KEK Measurements & Simulations on Morikawa Cells



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

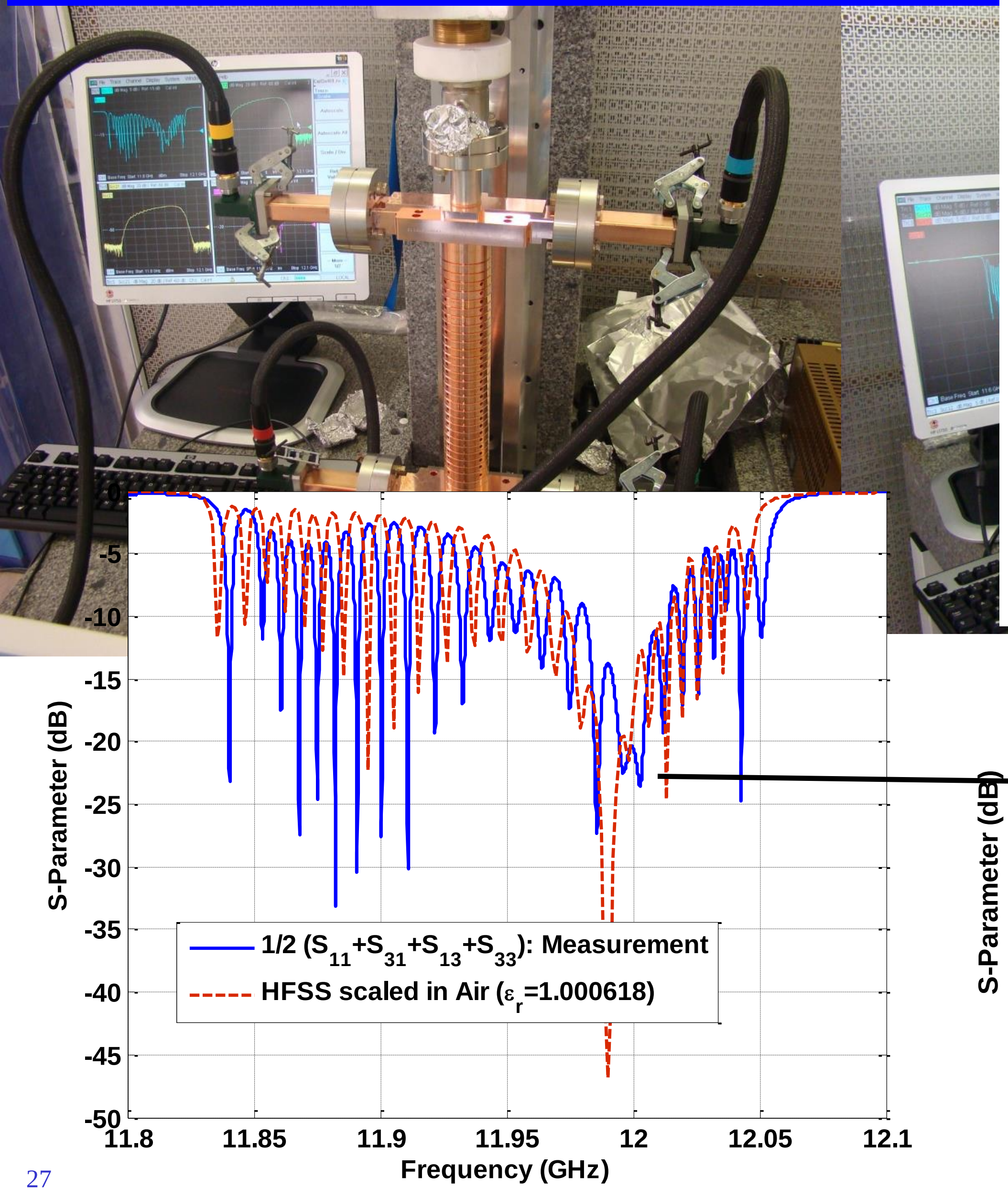
* HFSS scaled in air using ε_r=1.000618

§This cell is the *actual* one –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

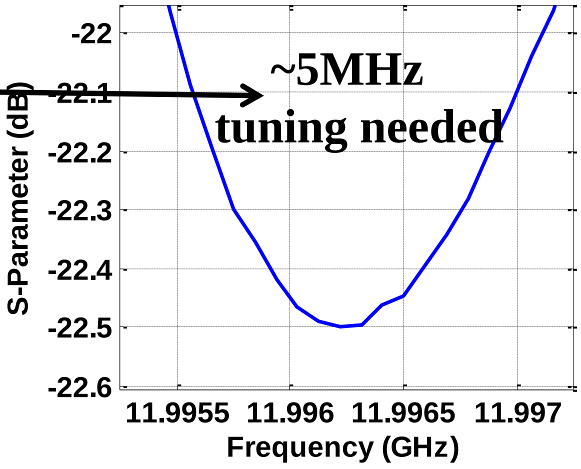
Indicative of ~2 µm fab tolerance!

Full Structure S_{21} Measurement



Overall Status

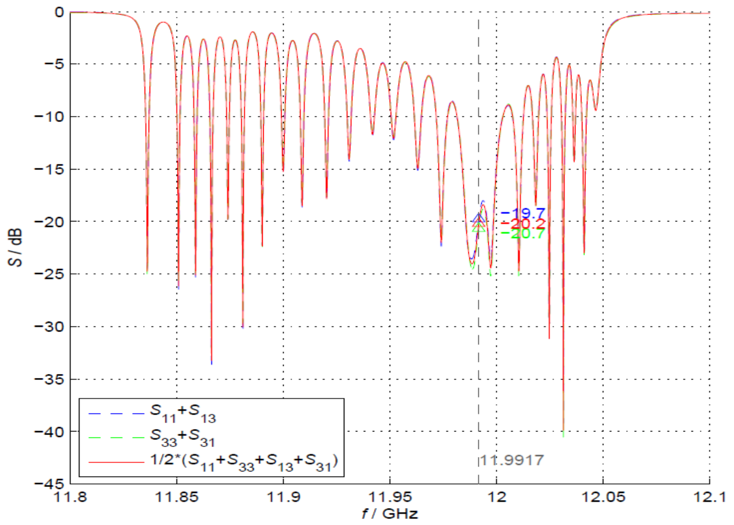
- Complete CLIC_DDS_A has been diffusion bonded at *Bodycoat*.
- Brazing of cooling block (blocks, tubes and caps) is complete
- Tuning studs recently brazed (tuned in Feb 2014)
- Structure will be high-power tested at CERN in 2015 (tbd) to assess ability to sustain high gradients



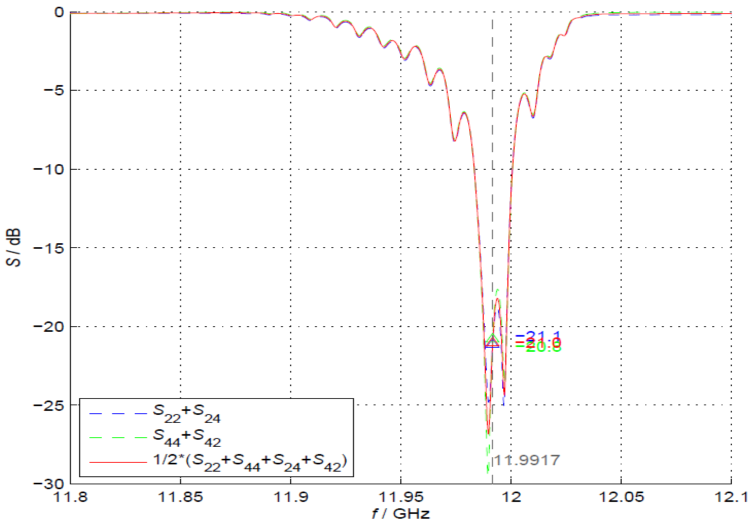
~5MHz tuning needed

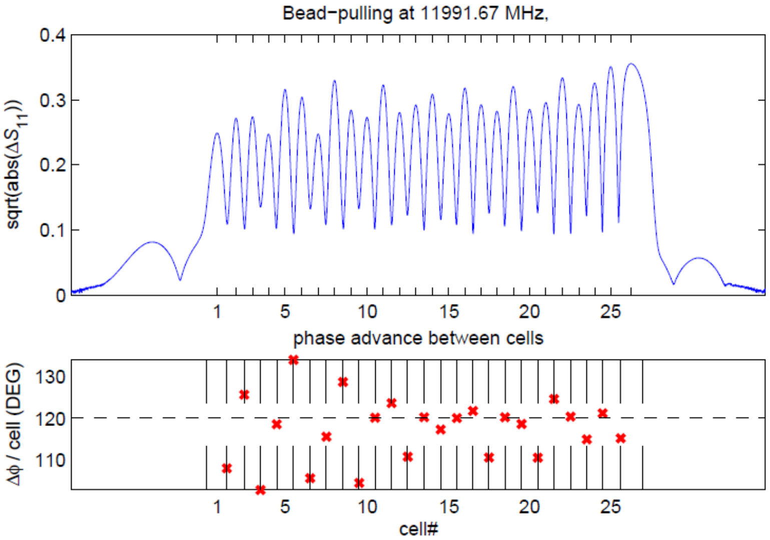
S_{11} Measured Prior to Tuning (Feb 2014)

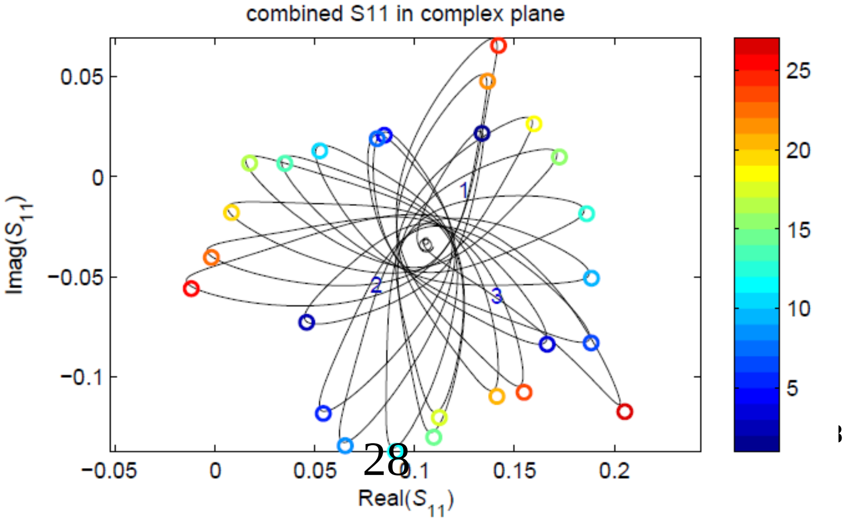
Reflection at the input



Reflection at the output

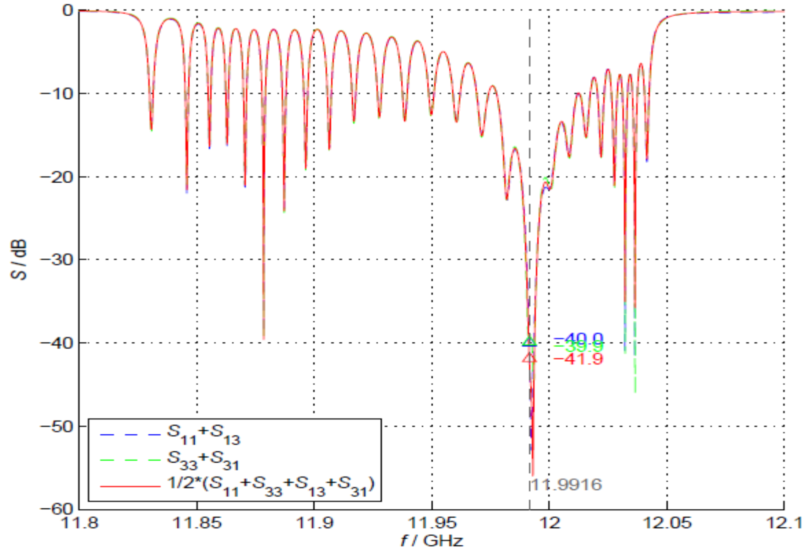




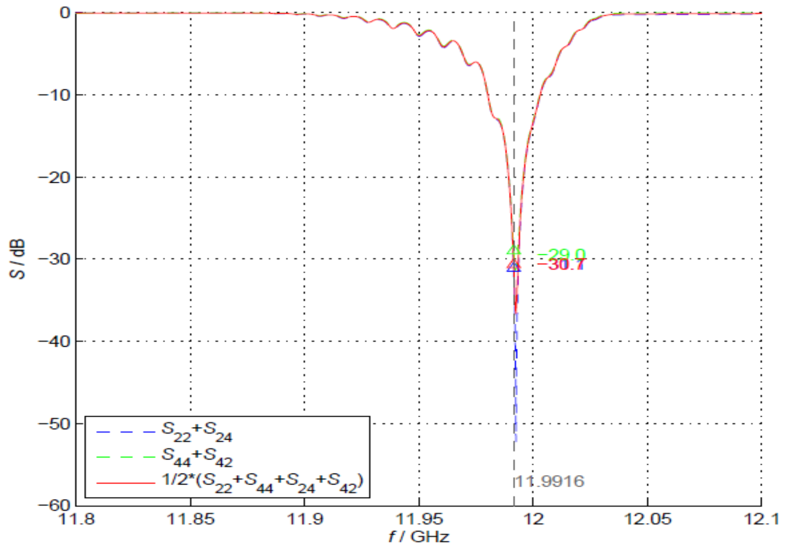


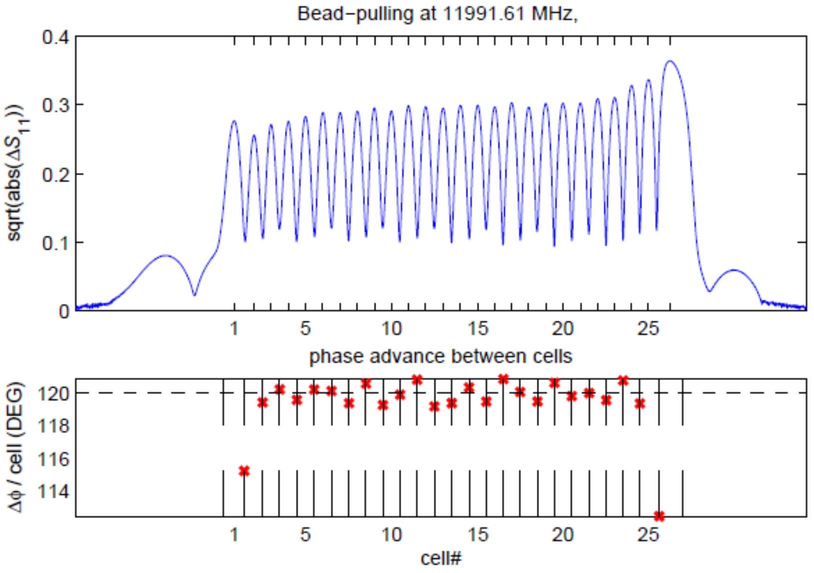
S_{11} Measured Afer Tuning (Feb 2014)

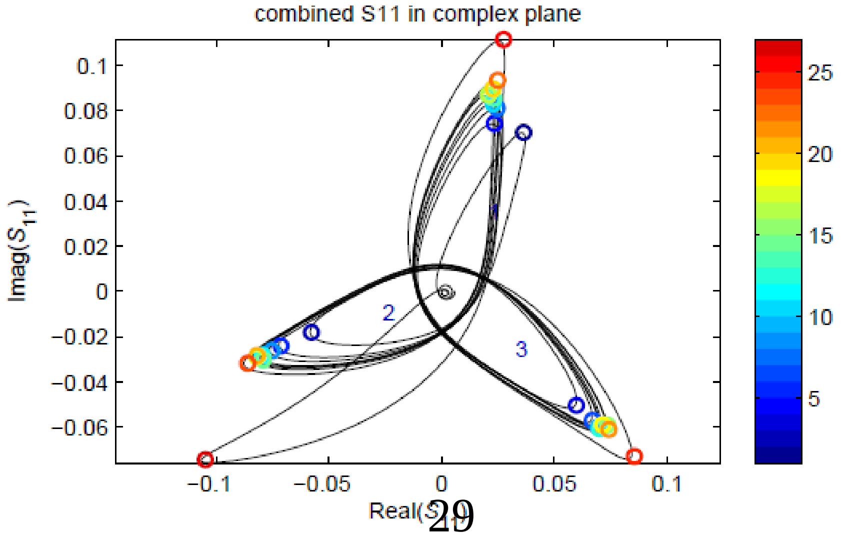
Reflection at the input



Reflection at the output







II. Final Remarks

- A CLIC_G baseline structure has met breakdown parameters in unloaded conditions.
- Compact DDS provides efficient wakefield damping for linear collider and light source applications -with reduced and de-localized loads
- Built-in BPM facility of HOMs in DDS provide a unique means of tracking beam and structure alignment. Also, DDS requires less loads than CLIC_G (requires loads either end rather than at each cell)
- Mechanical design takea into account all requirements on RF, beam physics, machining, assembly, installation and operation
- Beam Dynamics simulation indicate that errors introduced in fabricating 140,000 structures provides randomization which aids in preservation of beam quality (emittance dilution minimised)
- Choke mode structure provides an efficient means of suppressing HOMs
- Fruitful collaboration with several institutes has been established and it is essential to develop X-band RF structure production technology
- Single structure has recently (Feb 2014) been tuned in readiness for high power/gradient testing

II. Resource on HG Structures

- ➢*Collation of selected papers from:*

X-band structures, beam dynamics and sources workshop (XB-10)
Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
- Special volume devoted to X-Band Accelerators:
Volume 657, Issue 1, 21 November 2011, Eds, Chattopadhyay, S., Jones, R.M.
(http://www.sciencedirect.com/science/journal/01689002/657/1)

Selected 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., Ph.D. Thesis, 2011**

ICFA Beam Dynamics Mini-Workshop

XB-10

X-BAND RF STRUCTURES, BEAM DYNAMICS AND SOURCES WORKSHOP

COCKCROFT INSTITUTE

30th November - 3rd December 2010

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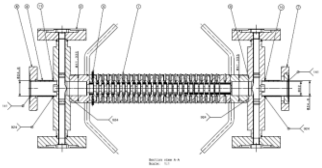
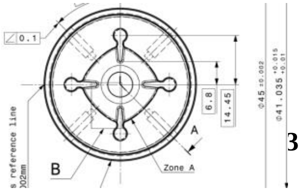
www.cockcroft.ac.uk/events/XB10





Final Remarks on HG Structures

- CLIC_G, DDS and Choke mode-based wakefield suppression structures are relatively mature –although considerable experimental verification is needed:
    - The baseline design, CLIC_G provides heavy damping (Q~10) of every cell in which dielectrics are located in immediate vicinity of coupling slots.
    - Choke mode suppression has some impact on fundamental mode Q and also some potential for higher order mode issues. Relatively simple to fabricate.
    - DDS allows remote location of (reduced) HOM loads. Built-in BPM and structure diagnostic. Sensitivity to fabrication errors –randomisation helps. Less rf loads needed (~22 less per 22 cell cavity)