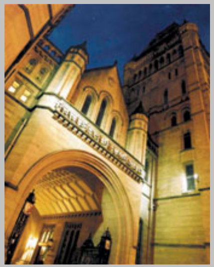
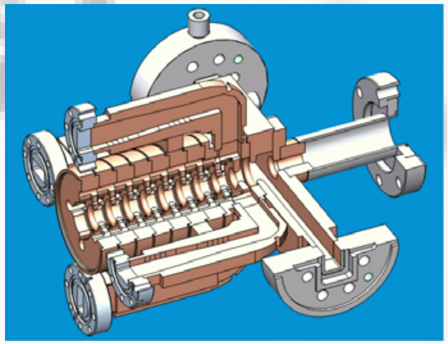


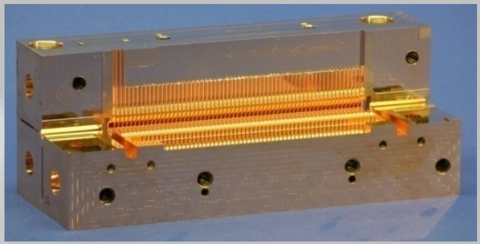
HOM Mitigation: Part II

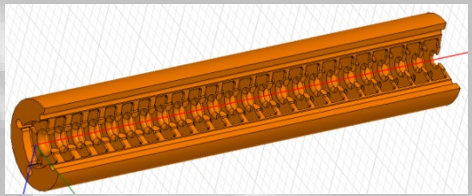
Roger M. Jones

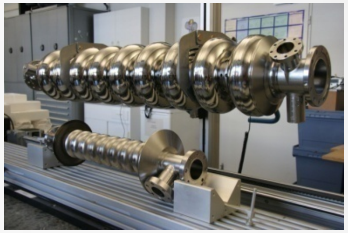
The University of Manchester

and the Cockcroft Institute









CAS RF For Accelerators
in collaboration with the University of Aarhus
8th – 17th June 2010, Ebeltoft, Denmark.

Overall Overview

1. **Review of features of wakefields and HOMs.**
2. **HOM mitigation in main accelerating structures of Normal Conducting (NC) High Gradient Linear Colliders –CLIC, NLC and light sources apps.**
3. **HOM mitigation in Superconducting RF (SCRF) Cavities and modules for linear colliders –ILC.**
4. **HOM mitigation in Energy Recovery Linacs**
5. **HOM in crab cavities –ILC, LHC.**
6. **Short summary, closing remarks**

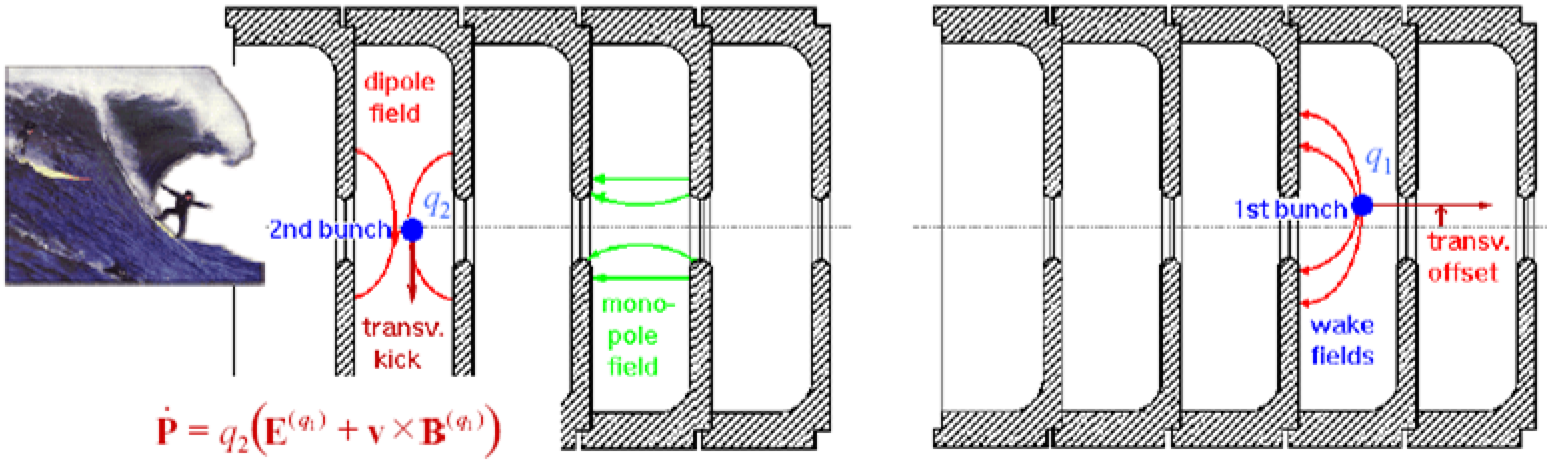
NC

Mainly SC

1. Rationale for Wakefield Suppression

- Charged particle beam excites parasitic modes
- Why damp these modes?
- Here we focus on linear collider 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

1. Wakefields Fundamentals

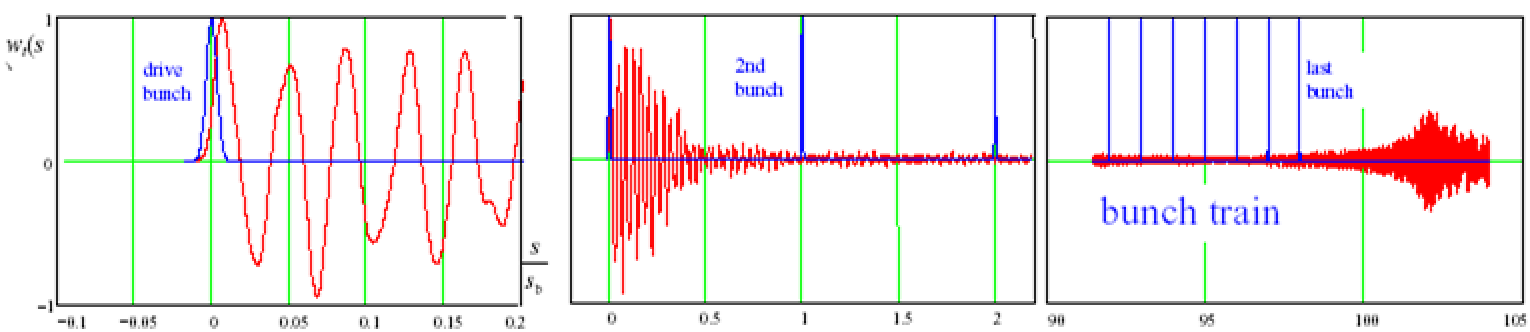


$$\dot{\mathbf{P}} = q_2\left(\mathbf{E}^{(q_1)} + \mathbf{v}\times\mathbf{B}^{(q_1)}\right)$$

dipole modes → lowest order contribution to transverse momentum

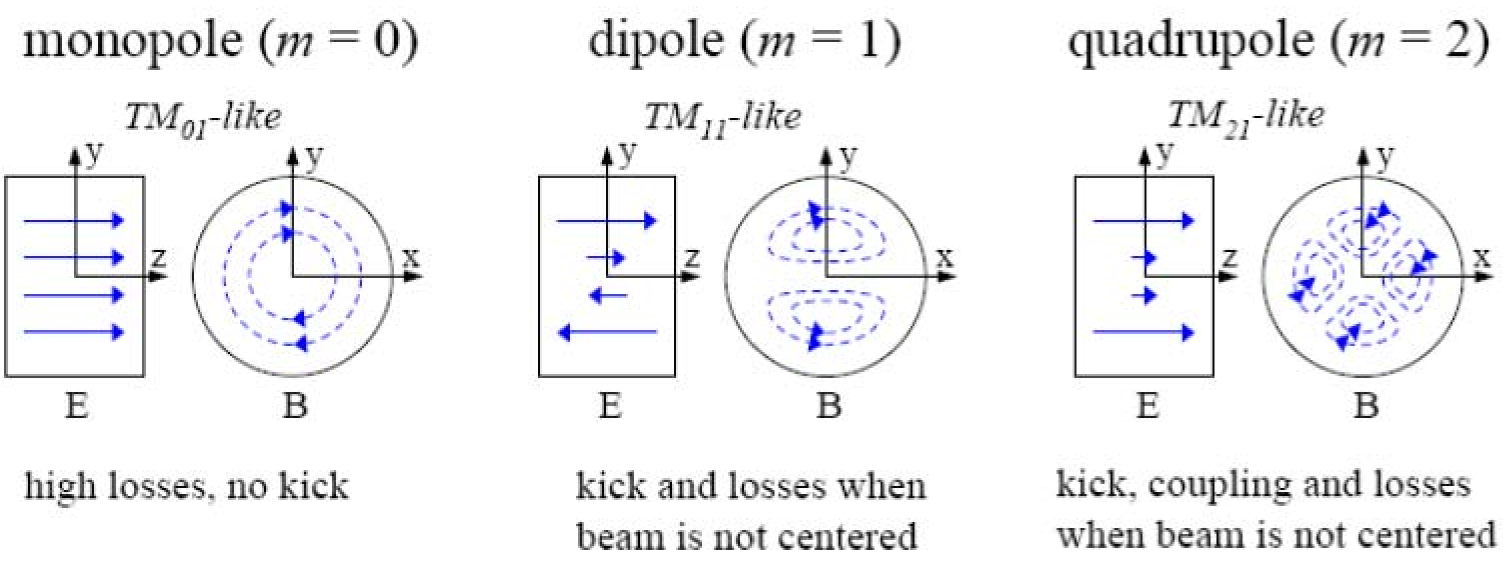
integrated transv. momentum: $\Delta \mathbf{P}_t = \frac{q_1 q_2}{c_0} w_D(s)\,\mathbf{r}_{1t}$ linear accelerators: $w'_D(s) = \frac{w_D(s)}{\text{length}}$

dimension: V/(Cm²)

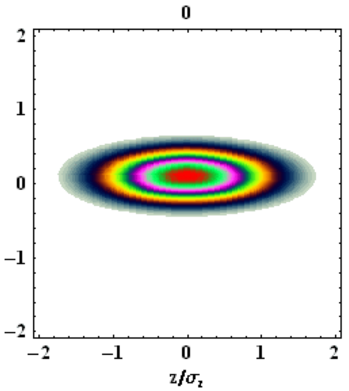


1. Mode Multipoles

-Focus mainly on dipole long-range transverse wakes



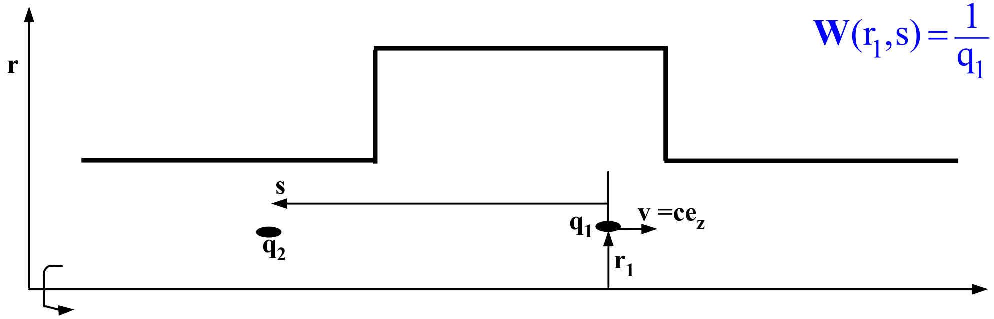
1. Features of Wakefields



Contours indicate density of original Gaussian distrn.

BBU Due to Short-Range 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 ($F_\perp$) is much simpler and this defines W(s), the wakefield:**



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

$$\Delta\mathbf{p}=q_1q_2\mathbf{W}(s)$$

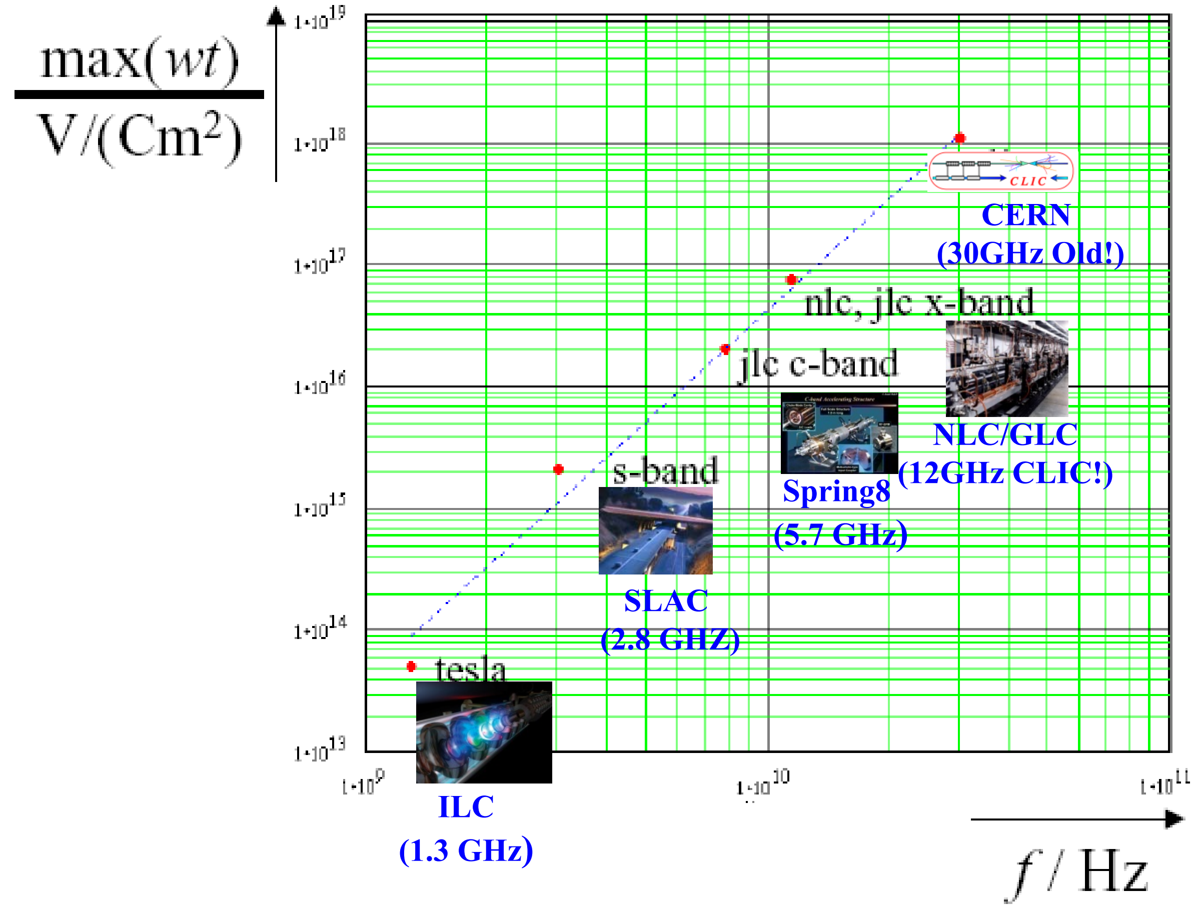
- **Long range wakes are suppressed by careful detuning and damping.**

1. Comparison of Wakes in Various Accelerators

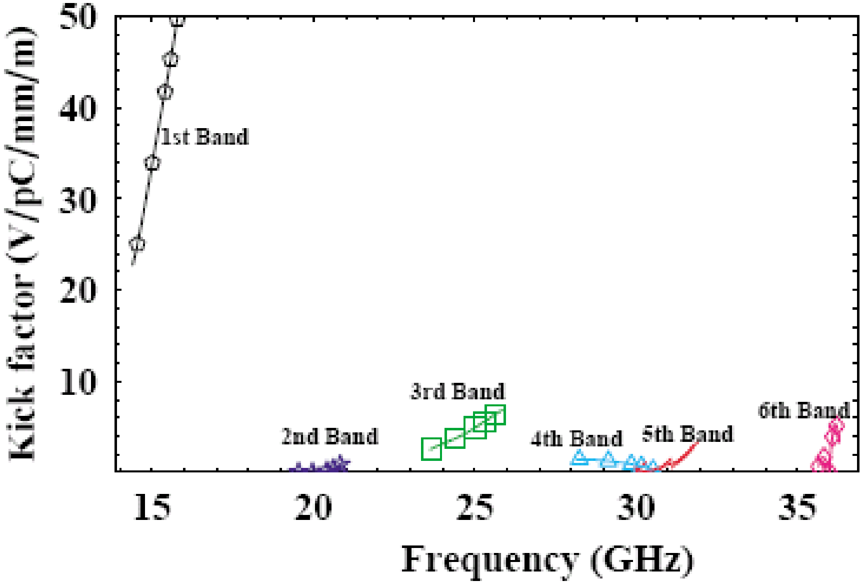
➢**Superconducting TESLA-style linacs have large cell apertures (~ 35 mm)**
=> smaller wakes. ILC Choice!

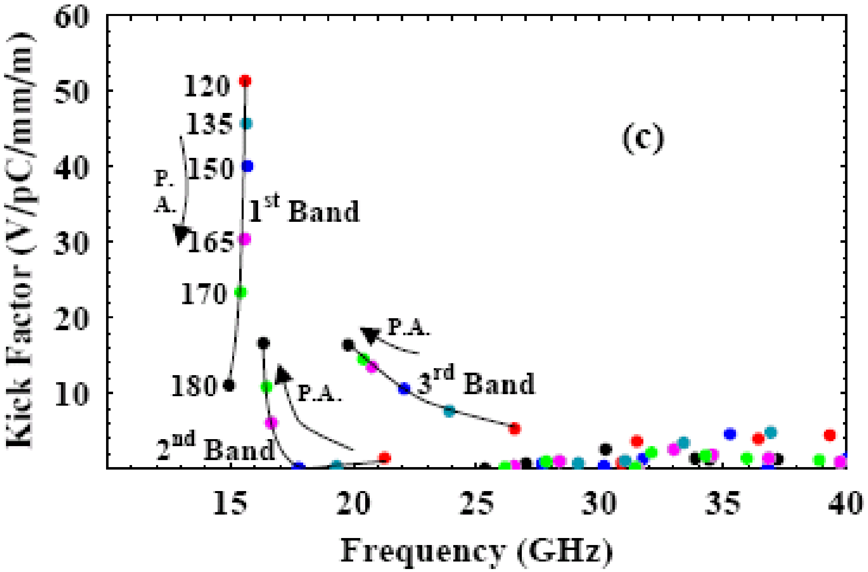
➢**NLC/GLC warm X-band linacs have small irises (~ 4 mm radius) =>larger wakefield.**

➢**CLIC has even smaller irises (~3 mm)! => larger wakes**
=> needs heavy damping (Q~10) of dipole modes or can use moderate damping (Q~500-100) and detuning?



1. Band Partitioning



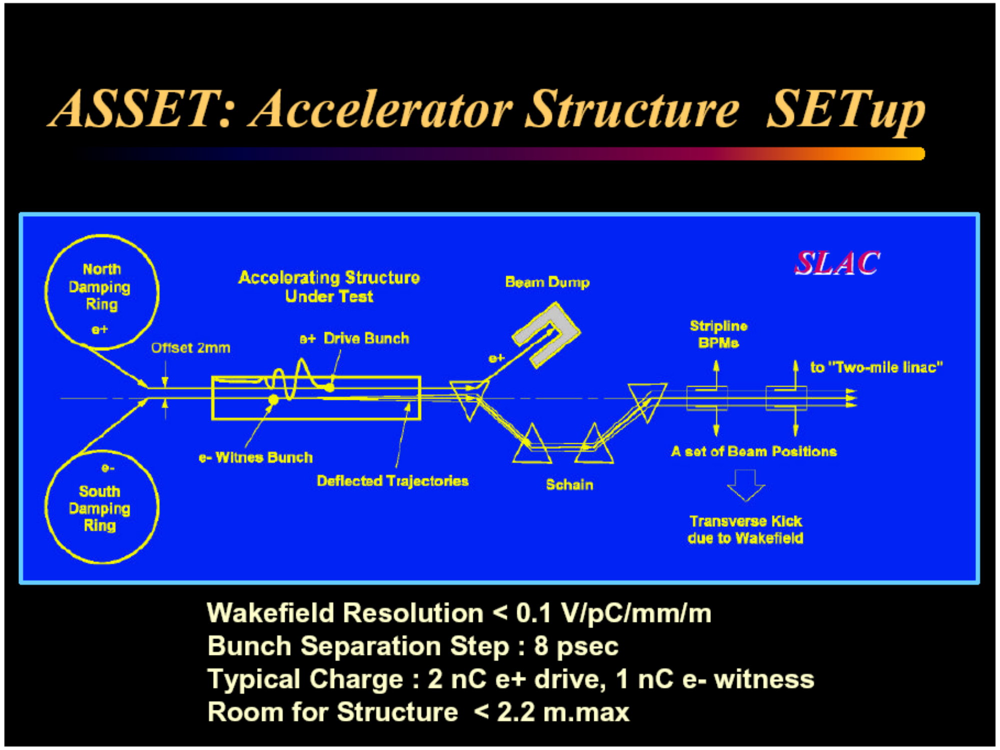


- Band partitioning of kick factors in 206 cell DDS1 X-band structure (f_{acc}=11.424 GHz). Largest kick factors located in the first band. Third and sixth bands although, an order of magnitude smaller, must also be be detuned along with the 1st band.
- CLIC design f_{acc} =11.9942 GHz shifts the dipole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

1. Measurement of Wakefields/HOMs



- $W_\perp$ 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 $\zeta = e^2 L_s n_d \exp(-\omega^2\sigma^2/c^2)$

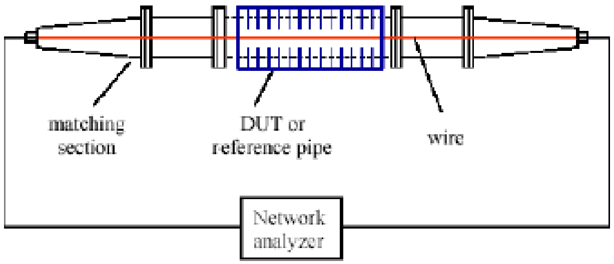
- Electron bunch serves as the witness bunch
- In traversing the DUT, the witness bunch is deflected by the wake function generated by the positron drive bunch.
- Witness bunch passes though chicane and down linac where trajectory is recorded by BPMs
- The transverse wake function is determined by measuring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

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

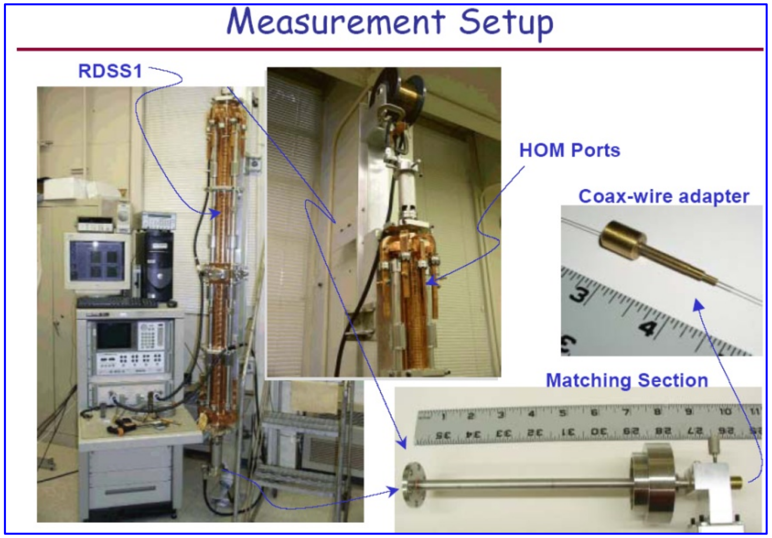
Ref: R. M. Jones, *Wake field Suppression in High Gradient Linacs for Lepton Linear Colliders*, Phys. Rev. ST Accel. Beams 12, 104801, 2009

1. Determination of HOMs in Structure via Stretched Wire Measurement

- Simulate beam by propagating pulse along wire
- Time domain =>measure distortion of current pulse
- Frequency domain =>measure S parameter (S_{21})
- Centered wire =>monopole mode
- Offset wire => dipole mode
- Method proposed by Matt Sands (~1974)
- Advantages
  -fast, inexpensive method to characterize beam impedance, loss factors, wakefield
  -does not require SLAC linac!



Schematic of Experimental Setup



- ➢Illustrated is an X-band Set-up at SLAC.
- ➢Designed as part of the GLC/NLC programme.
- ➢Able to accommodate 1.8m structures.
- ➢Several other configurations in use internationally.

Ref: F. Caspers, *Bench methods for beam-coupling impedance measurement* (Lecture notes in beams: intensity limitations vol 400) (Berlin, Springer, 1992)

Wire Wakefield Measurement Technique

2.1 Overview: NC X-Band Wakes

Two Main Parts:

1. **Past experience in X-Band Linear Accelerating Structure Design: NLC /GLC (Next Linear Collider/Global Linear Collider).**
   -Vast (more than 15 years) experience obtained in a collaborative (SLAC/KEK/FNL) design and fabrication of a host of test structures.
   -Principles of wakefield suppression and built-in structure diagnostic discussed

Earlier Project

2. **Alternate Design for Wakefield Suppression for CLIC: Initial studies at Cockcroft Inst./Univ. Manchester**
   -Method described in 1 applied to CLIC

Ongoing Major Intl. Project

2.1 Preservation of Luminosity

NLC Luminosity a factor of several 10,000 larger Than The SLC

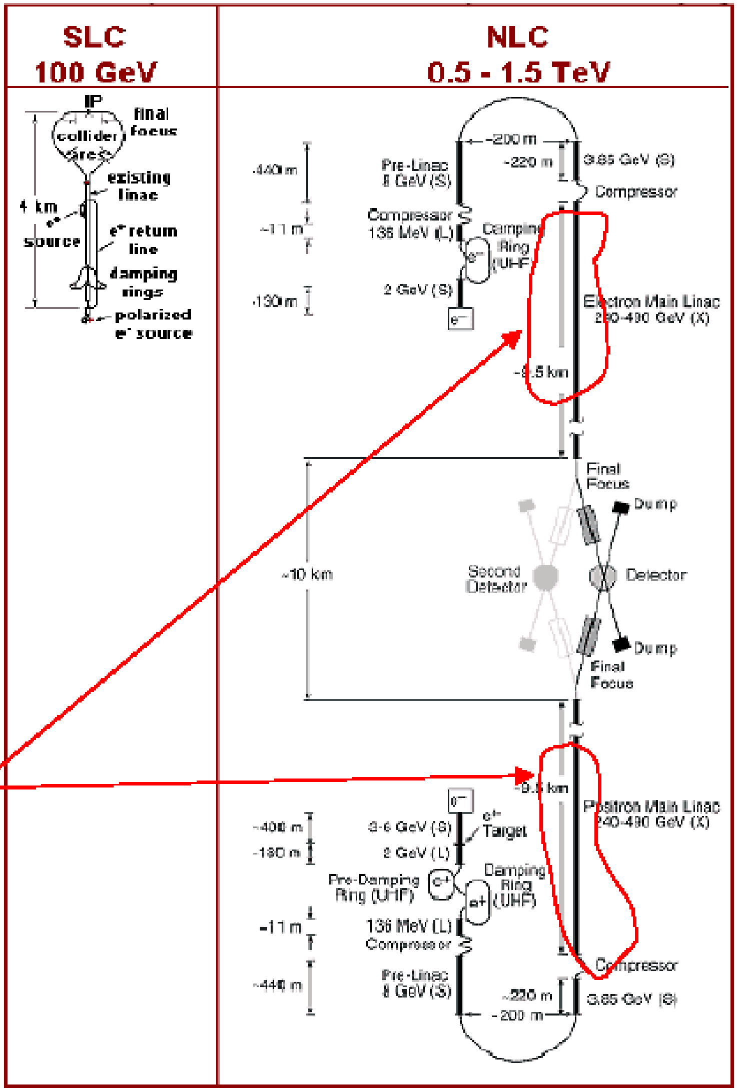
$$L = \frac{f_{rep}\, n_b N^2}{4\pi\, \sigma_x \sigma_y} H_D \Rightarrow \frac{2 P_b f_{rep}}{4\pi E_{cms}} \frac{N}{\sigma_x \sigma_y} H_D$$

L is luminosity (~3×10^{34}), n_b is the number of bunches (192), f pulse rep rate (120), N number of particles per bunch (~$.7\times10^{10}$)
H_D disruption enhancement factor , σ_x / σ_y tranverse beam size ratio (~300)

L increase arises from:

*More beam power from long bunch train:
192 bunches. Factor 200
⇒ ***Long-range wakefield control is crucial to prevent BBU and emittance dilution***

*Larger cross-sectional densities: $N/(\sigma_x\sigma_y)$
⇒Adiabatic damping (beam is squeezed in momentum space). Factor ~5
⇒Strong focusing from the lattice. Factor ~4
⇒ Smaller normalized emittance at IP. Factor ~15-30



R.M. Jones, UCLA, May 7, 2003

2.1 Outline

- Why damp long range wakefields? BBU and Emittance dilution issues
- Analysis of DDS (Damped and Detuned Structures
Modal and spectral analysis
- ASSET results: theoretical prediction (with no asposteri fittings) vs Experiment:
DDS1, RDDS through to H60VG4A/B
- Influence of fundamental coupler on wakefield
- Stack measurements of RDDS
- Built-in diagnostic properties of RDDS
- Influence of fabrication errors on BBU and emittance dilution
- New high phase advance structures (TW 5π/6 and SW π)
- TW and SW designs and interleaving of frequencies
- Limited local damping and manifold damping

2.1 Review of General Methods of Wakefield HOM Damping

1. **Strong Damping** (Q~10) => loss in the shunt impedance of the monopole mode.

a) Magnetic coupling –azimithal slots (kidney slots)

b) Electric coupling – longitudinal slots

2. **Resonant suppression**

a) single frequency: $f_{dipole} = (n/2)\ f_{bunch}$ (zero-mode crossing)

b) multiple frequency, beat-note: $f_{dipole1} - f_{dipole2} = n\ f_{bunch}$

3. **Non-resonant suppression** –Detuning

a) Rectangular Kdn/df (kick factor weighted mode density) => sinc function wake

b) Gaussian Kdn/df => Gaussian wake function

c) Truncation of Gaussian necessitates light damping in addition to detuning

d) Less sensitivity to frequency errors

e) Less impact on fundamental mode shunt impedance

2.1 General Aspects of Detuning

Gaussian density distributions

- Kick factor weighted density function: $Kdn/f \sim \exp[-(\omega-\omega_0)^2/2\sigma_\omega^2]$
- Ideally: $W(t) \sim \exp(-\sigma_\omega^2 t^2/2)$

- <u>Advantages over other methods</u>

1. It is non-resonant and hence it does not freeze collider operation a bunch spacing other than the minimum bunch spacing.
2. Wakefield decreases rapidly and monotonically
3. It permits an error function interpolation with relatively sparse parameters

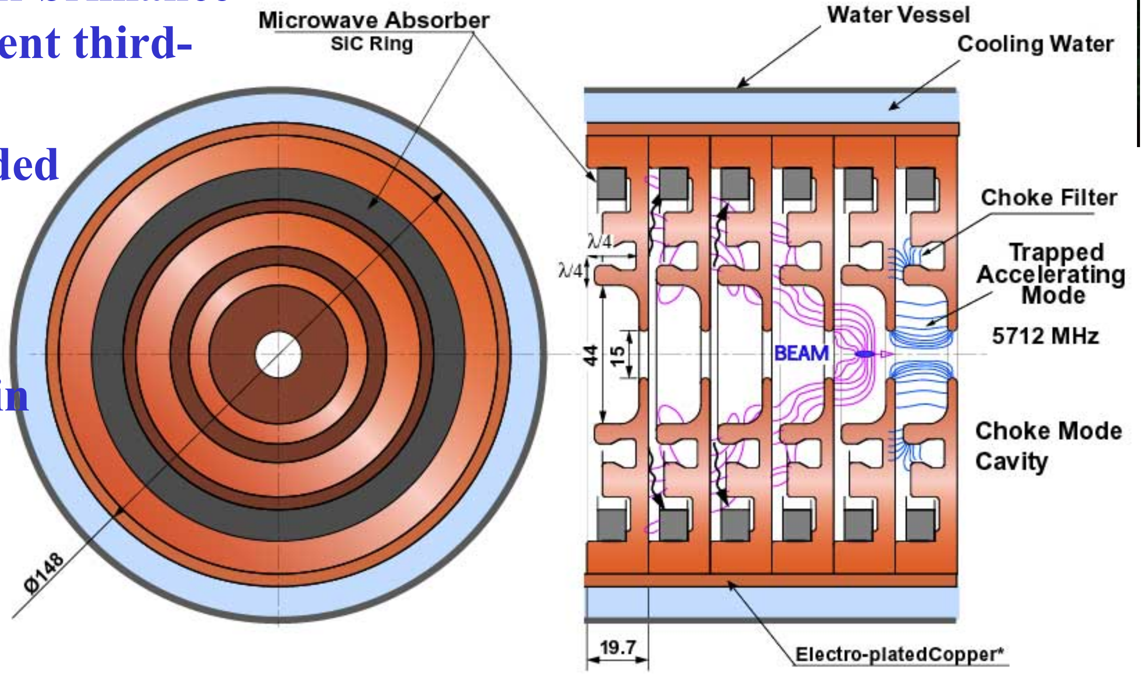
- <u>Disadvantages</u>

1. Gaussian distribution is not limited and thus eventually it is truncated. This truncation gives rise to a sinc-like (=sin(x)/x) wake which curtails the rapid fall-off at a level dependent on the truncation point
2. The finite number of cells => finite number of modes => partial recoherence of wake-field starting at a time $t \sim 1/\delta f_{max}$ (where δf_{max} is the maximum separation of modes). Also, with damping there is another coherence point, further out, at $1/\delta f_{min}$ (where δf_{min} is the minimum separation of modes, which lies in the centre of the Gaussian)

2.1 C-Band Wakefield HOM Suppression

SPring-8 (Super Photon ring-8 GeV)

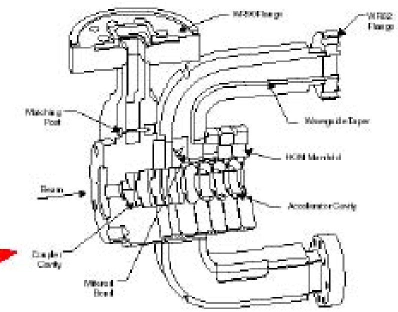
- Synchrotron radiation facility, including compact SASE Source in Japan
- High peak-brilliance soft X-ray FEL project for R&D A
- Angstrom X-ray laser facility.
- SCSS (SPring-8 Compact SASE Source)will provide six order of magnitude peak-brilliance enhancement compared to the current third-generation 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 (λ/4)
- 35-40 MeV/m, why not higher?



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)

2.1 X-Band DDS Accelerators Installed in NLCTA at SLAC

- Consider Damped and Detuned Structures at 11.424 GHz
- Several built and installed in the SLAC NLCTA facility
- High gradient structures (eventually reaching >65 MV/m)
- Several versions fabricated in successful Japan/USA collab.
- Nomenclature JLC/NLC or GLC/NLC are equally valid.
- CLIC now uses similar technology at 11.994 GHz.



Cross-Sectional View of Input End of DDS (Damped Detuned Structure)

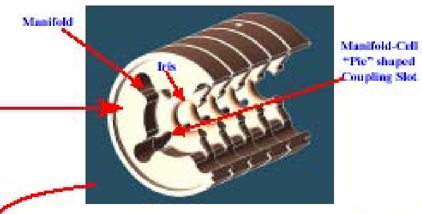
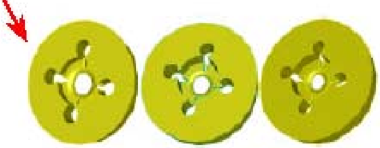
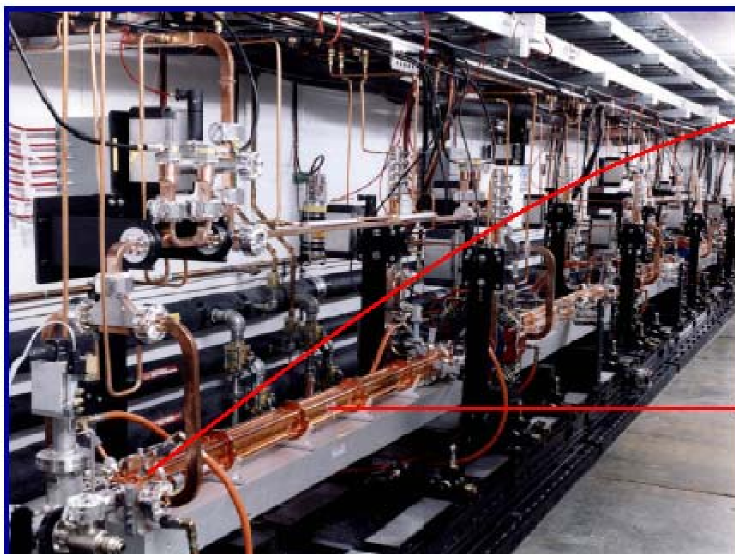


Illustration of Several Cells in DDS

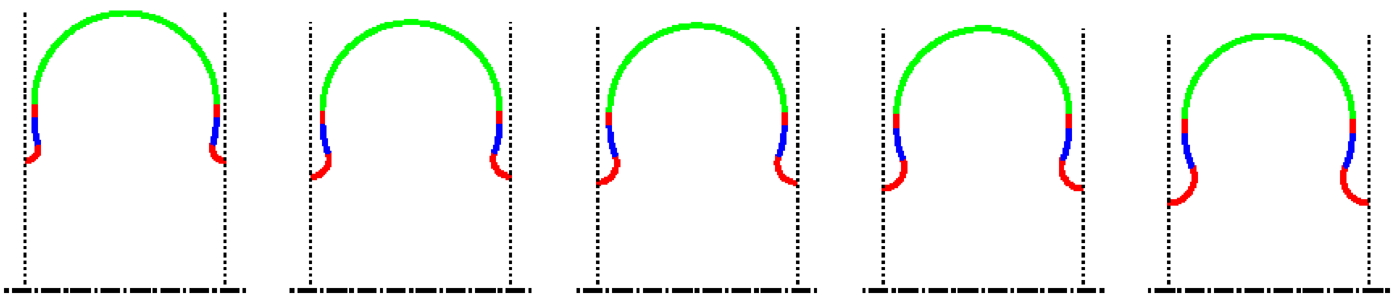




NLCTA (Next Linear Collider Test Accelerator)

2.1 Tapering (Effects Detuning) of X-Band RDDS Accelerator

X-Band Round Detuned Structure (param-c), a/λ=0.18



Cell 001	Cell 052	Cell 103	Cell 154	Cell 206
a = 5.65953mm	a = 4.97649mm	a = 4.70741mm	a = 4.45370mm	a = 3.81706mm
Q = 8300.38	Q = 7970.96	Q = 7846.88	Q = 7733.49	Q = 7462.76
R = 76.8596 MΩ/m	R = 86.7337 MΩ/m	R = 90.6774 MΩ/m	R = 94.3869 MΩ/m	R = 103.476 MΩ/m
R/Q = 9259.76	R/Q = 10881.21	R/Q = 11555.85	R/Q = 12204.95	R/Q = 13865.69
V_g/c = 0.1135	V_g/c = 0.0744	V_g/c = 0.0612	V_g/c = 0.0499	V_g/c = 0.0272
E_s/E_a = 3.00790	E_s/E_a = 2.51850	E_s/E_a = 2.41357	E_s/E_a = 2.32035	E_s/E_a = 2.18890

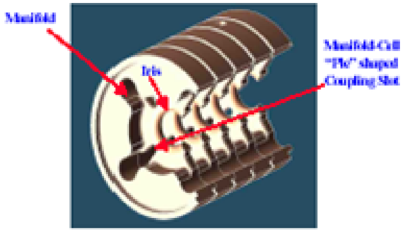
- **Detuning effected by reducing the iris down the structure.**
- **For example, enforce an erf (error) function variation of iris with cell number, gives rise to Gaussian wake supression.**
- **Wake ~ Kdn/df (kick factor weighted density function)**

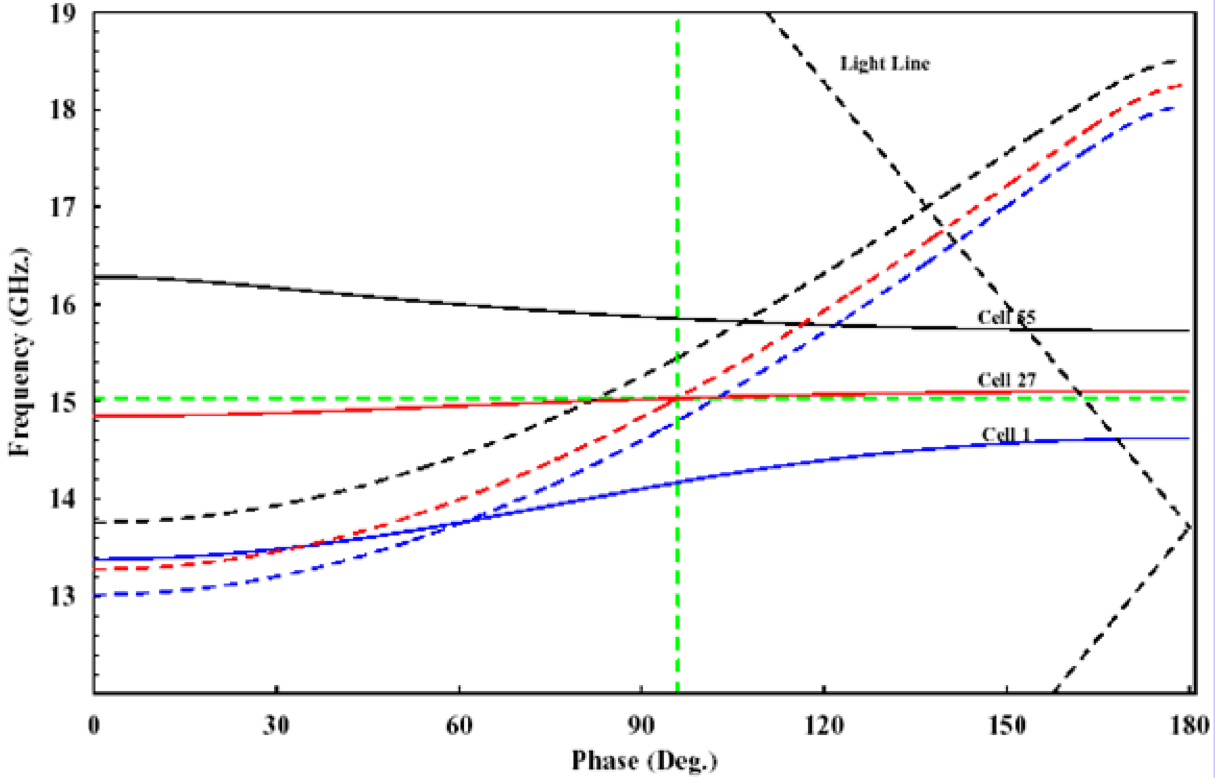
2.1 Physics of Manifold Mode Coupling to HOM Dipole X-Band Modes

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





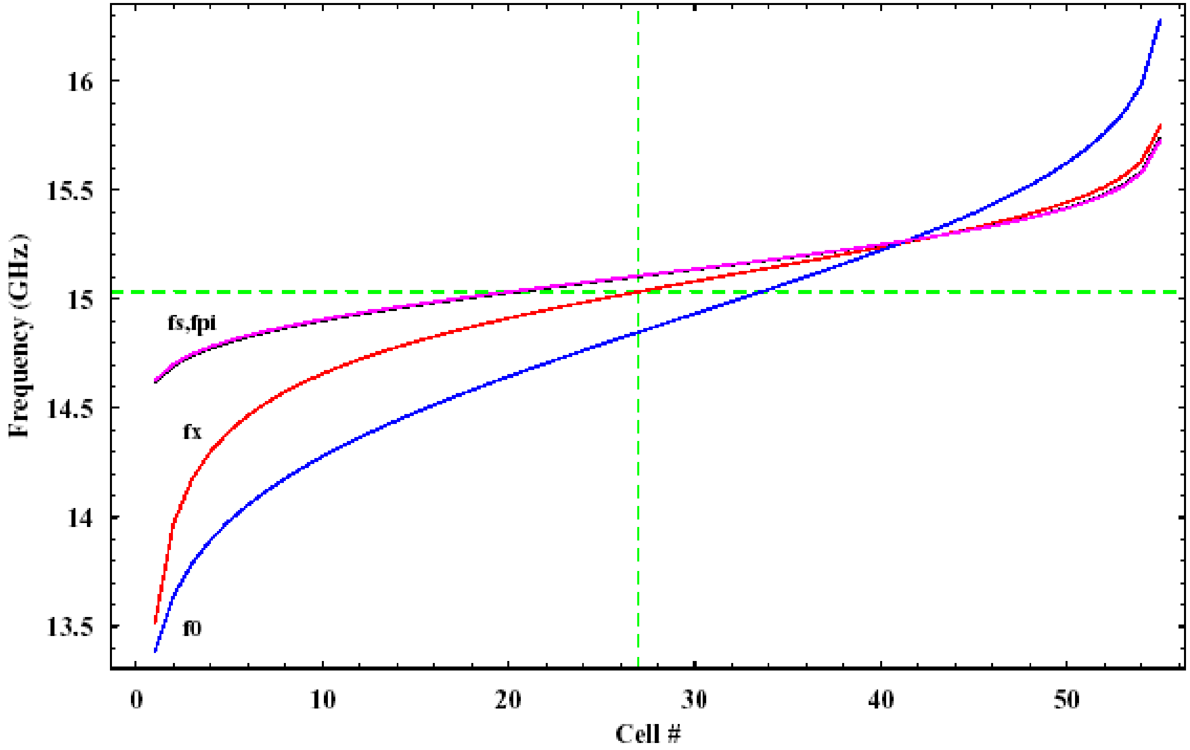
2.1 Coupling Along Complete Structure

* In general, the beam propagates down the accelerating structure and is localized to a limited number of cells
(it becomes progressively more localized as it moves down the structure towards the zero group velocity point)
* It couples to the manifold several cells away from the excitation point.

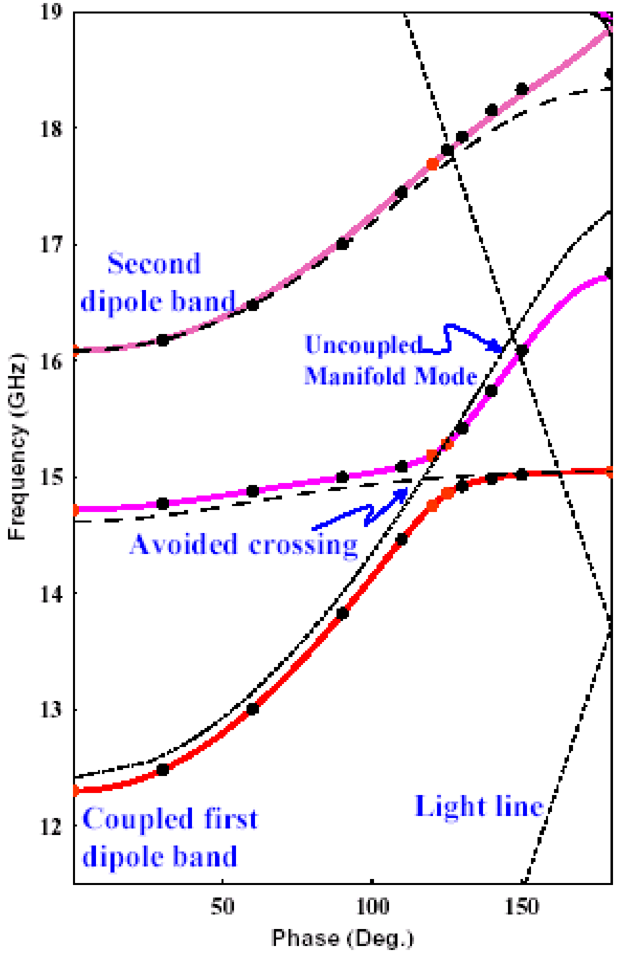
Mode Synchronous With the Light Line is Denoted: **fs**

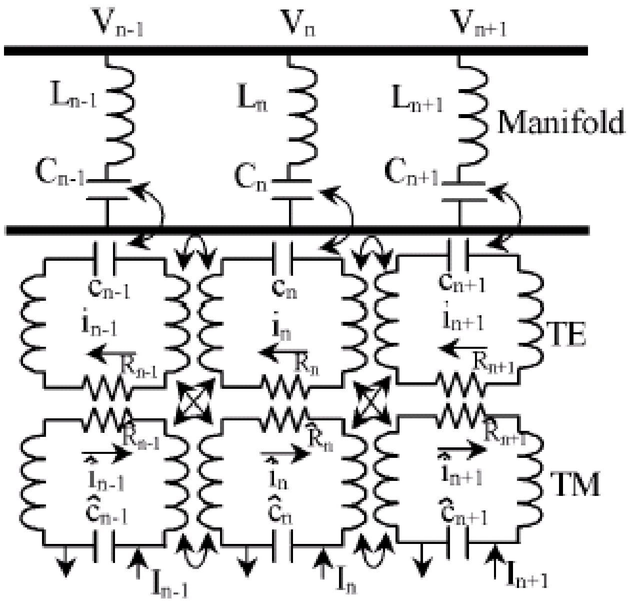
Mode Corresponding to Crossing of Manifold and Cell-Mode by: **fx**

Zero and Pi Modes by: **f0, fp**



2.1 Circuit Model of X-Band 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.

Ref: ***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**.

2.1 Circuit Model Equations

Coupling Between Manifold-Cell

$$V_n = -j\left(I_n / C_n + i_n \kappa_n / \sqrt{C_n c_n}\right)/\omega$$

$$v_n = -j\left(i_n / c_n + I_n \kappa_n / \sqrt{C_n c_n}\right)/\omega$$

Matrix Elements

$$R_{nn} = -2\cos\phi_n, \quad R_{nn\pm1} = 1$$

$$\cos\phi_n = \cos\phi_{0n} - \alpha_n\left(\pi L / c\right)^2 F_n^2 / \left(F_n^2 - f^2\right)\operatorname{sinc}\phi_{0n}$$

$$\phi_{0n} = \left(2\pi L / c\right)\sqrt{f^2 - F_{cn}^2}$$

$$H_{nn} = 1/f_n^2 + \Gamma_n^2 / \alpha_n / \left(F_n^2 - f^2\right)$$

$$H_{nn\pm1} = \eta_{n\pm1/2} / \left(2 f_n f_{n\pm1}\right)$$

$$H_{nn\pm1} = \pm\eta_{x,n\pm1/2} / \left(2 f_n \hat{f}_{n\pm1}\right)$$

$$\hat{H}_{nn} = 1/\hat{f}_n^2, \quad \hat{H}_{nn\pm1} = -\hat{\eta}_{n\pm1/2} / \left(2 \hat{f}_n \hat{f}_{n\pm1}\right)$$

$$G_{nn} = \Gamma_n\left(\pi L / c\right)^2 F_n^2 / \left(F_n^2 - f^2\right)\sqrt{2\operatorname{sinc}\phi_{0n}}$$

Network Equations in Matrix Form:

$$RA = Ga$$

$$\left(H - 1/f^2\right)a + H_x \hat{a} = GA \left(= G R^{-1} G a\right)$$

$$\left(\hat{H} - 1/f^2\right)\hat{a} + H_x^t = B/f^2$$

- In the 9-parameter model each parameter is determined from MAFIA or Omega3 simulations to produce Brillouin diagrams for a limited number of fiducial cells.

- The remaining cells are obtained by interpolation and non-linear error function (Erf) fits.

2.1 Determination of Parameters

•There are nine parameters to be determined (5 associated with the cells and 4 with the manifold).

•These are determined by specializing to uniform structures as we did in the case of a DS. The dispersion curves for the three lowest modes are matched to those determined from simulations using MAFIA and Omega3:

$$\left[\overbrace{\left(\frac{1+\eta\cos\psi}{f_0^2}+\frac{\Gamma^2}{\alpha\left(F^2-f^2\right)}-\frac{1}{f^2}\right)}^{\text{TE Cell Mode}}\overbrace{\left(\frac{1-\hat{\eta}\cos\psi}{\hat{f}_0^2}-\frac{1}{f^2}\right)}^{\text{TM Cell Mode}}-\overbrace{\frac{\bar{\eta}^2}{f_0^2\hat{f}_0^2}\sin^2\psi}^{\text{TE-TM Coupling}}\right]\overbrace{\left(\cos\psi-\cos\phi\right)}^{\text{Manifold Mode}}=$$

$$\underbrace{\left(\frac{F^2}{F^2-f^2}\right)^2\left(\frac{\pi L}{c}\right)^2\left(\frac{1-\hat{\eta}\cos\psi}{\hat{f}_0^2}-\frac{1}{f^2}\right)\sin\phi_0}_{\text{Coupling to Manifold}}$$

•Setting $\Gamma = 0$ it is evident that the above breaks up into 3 equations: $\cos\psi = \cos\phi$, the manifold equation, and a two band dispersion relation

We require 9 points on the curves. Three dispersion are used and the 6 $\psi = 0, \pi$ points. This guarantees that the mode curves given by the circuit match the end points. The remaining 3 points are taken near the avoided crossing. They guarantee that the curves cross at the correct phase and that the shape of the avoided crossing is well represented (the coupling strength is determined in this region).

Thus we form:

$$\begin{bmatrix} D_1(p) \\ \cdots \\ \cdots \\ D_9(p) \end{bmatrix} = 0$$

where $D_n(p)$ represents the dispersion relation obtained from the nth ψ point and p represents 9 parameters.

These 9 coupled non-linear equations are solved for the 9 parameters and the 3 dispersion curves are obtained. This procedure was followed for 11 cells of DDS1 and intermediate cells are obtained by interpolation and error function fitting procedures.

2.1 Determination of Wake function

Firstly, consider the eigensystem without the driving beam: the source-less eigensystem:

$$Ha^p = \lambda_p a^p$$

H = Complete matrix of system where the coupling to the manifold is included (symmetric non-Hermitian) $\lambda_p = 1/f_p^2$ $a^p = i_p/\sqrt{c_p}$ $a^p . a^q = \delta_{pq}$

To obtain the solution in the presence of the driving current, the beam, we make an expansion over the source-less eigenfunctions. This enables the envelope of the wake function to be obtained as:

$$\hat{W}(s) = \left| \sum_p K_p \exp\left[k_p s \left(j - 1/(2Q_p) \right) \right] \right|$$

where the kick factors are given by:

$$K_p = \frac{\sum_n a_n^p \sqrt{K_s^n f_s^n} \exp\left(jn\phi_p \right) \sum_m a_m^p \sqrt{K_s^m f_s^m} \exp\left(-jm\phi_p \right)}{N f_p (1 - df_p/df) a^p \left(a^p \right)^{\dagger}}$$

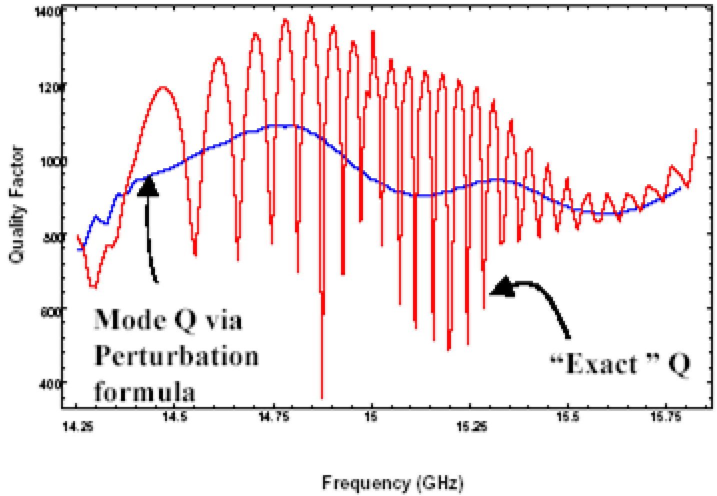
and $\phi_p = \omega_p L/c$ (L= length of structure), f_s^n is the nth synchronous frequency and K_s^n is the nth cell uncoupled kick factor.

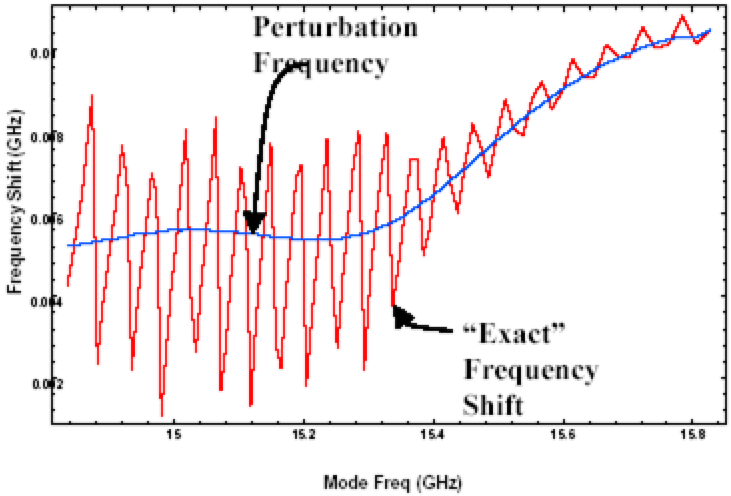
Also, the double band kick factor is obtained in a similar manner as:

$$K_p = \frac{\sum_n a_n^p \sqrt{\varepsilon^n K_s^n f_s^n}\exp\left(jn\phi_p\right)\sum_m a_m^p \sqrt{\varepsilon^m K_s^m f_s^m}\exp\left(-jm\phi_p\right)}{N f_p (1 - df_p/df) a^p \left(a^p\right)^\dagger}$$

However, the determination of the eigenfunctions becomes a complex process in which 612 eigenvectors are required to be carefully sorted. A straightforward perturbation solution does not yield sufficiently accurate results as in shown in the next transparency. Thus, in order to be able to routinely design (R)DDS it is necessary to utilize a new method, the Spectral Function

2.1 Perturbation Analysis





- The exact modal method reveals the Q and frequency shift to oscillate about the perturbed values (characteristic of an overcoupled system)

- Coupling to the manifold changes the modal Qs and frequencies of the linac.

2.1 Spectral Function Method

The sum over damped modes, which provides the main contribution to the transverse wake of the (R)DDS, is replaced by a Fourier-like integral of a spectral function over the propagation band of the manifolds.

Recall the circuit equations for the TE and TM cell amplitudes in matrix form:

$$\begin{pmatrix} \hat{H} & H_x^t \\ H_x & H\text{-}GR^{-1}G \end{pmatrix}\begin{pmatrix} \hat{a} \\ a \end{pmatrix} - \frac{1}{f^2}\begin{pmatrix} \hat{a} \\ a \end{pmatrix} = \frac{1}{f^2}\begin{pmatrix} B \\ 0 \end{pmatrix}$$

Here, H_x is a tridiagonal matrix with vanishing diagonal elements which describes the TE-TM cross coupling, R which describes propagation in the manifold is also tridiagonal and G, which describes the TE coupling of the cells to the manifold is diagonal. The elements of the column vectors are themselves N element vectors.

The above readily lends itself to a further condensed form:

$$\bar{H}\bar{a} - f^{-2}\bar{a} = f^{-2}\bar{B}$$

The drive beam represented by the N component vector B couples to the TM wave only:

$$B_n = \sqrt{\left(4\pi f_s^n / c\right) K_s^n L}\, \exp\left[-j2\pi\left(L/c\right)n\right]$$

where L is the periodicity of the cell. The transverse wake function (transverse potential per unit length) for a particle traveling behind a velocity c particle (per unit drive charge per unit witness charge) is written:

$$W(s) = \int Z(f - j\varepsilon)\exp\left[\left(2\pi j s/c\right)\left(f - j\varepsilon\right)\right]df$$

where ε is an infinitesimal quantity (required to ensure the integral is performed away from the real axis) and the wake impedance is given by:

$$Z(f) = \pi^{-1}\sum_{n,m}^{N}\sqrt{K_s^n K_s^m}\exp\left[\left(2\pi jL/c\right)f\left(n-m\right)\right]\tilde{H}_{nm}$$

with the 2N x 2N matrix given by:

$$\tilde{H} = \bar{H}\left(1 - f^2\bar{H}\right)^{-1}$$

Because W(s) is real we require Z(f) =Z*(-f*) for f in the lower half plane. Due to the presence of the manifold we find that Z is discontinuous across the real axis and thus cuts are introduced to ensure that Z remains single valued on the physical sheet. It also an even function of f in the complex plane Z(f) = Z(-f).

2.1 Spectral Function Regimes

1. **Zero Damping (Pure Detuning)**

$$W(s)=\theta(s)\sum 2K_p\sin\left(k_p s\right)$$

Here s is the distance behind the bunch, θ(s) is the unit step function and

$$k_p=\frac{2\pi f_p}{c}$$

2. Weak Damping

$$W(s)=\theta(s)\sum 2K_p\sin\left(k_p s\right)\exp\left(-\frac{k_p}{2Q_p}s\right)$$

3. **Strong and Moderate Damping**

$$W(s)=\theta(s)\int_{cut} S_p(f)\sin\left(k_p s\right)df$$

The spectral function technique covers a broad class of regimes: 1 and 2 are special cases of 3.

2.1 Determination of Cell Offset From Energy Radiated Through Manifolds

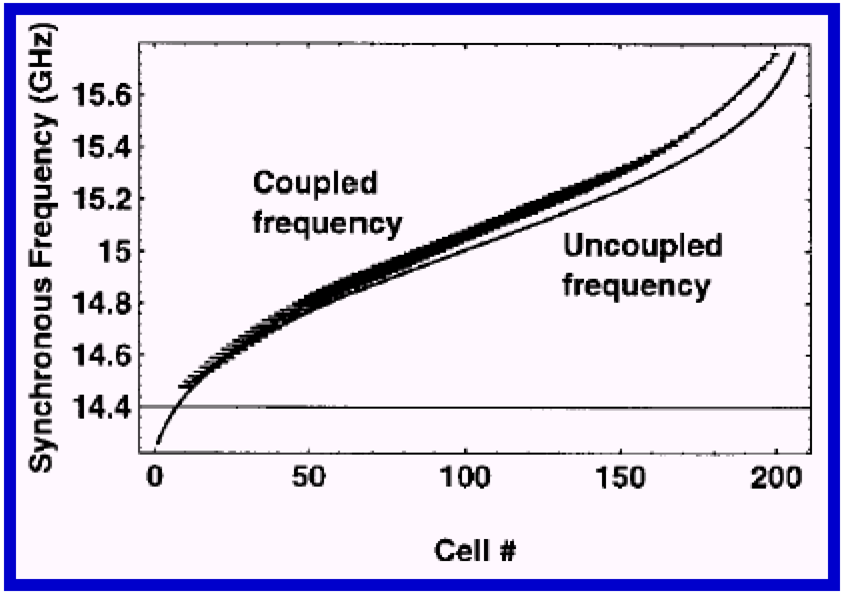
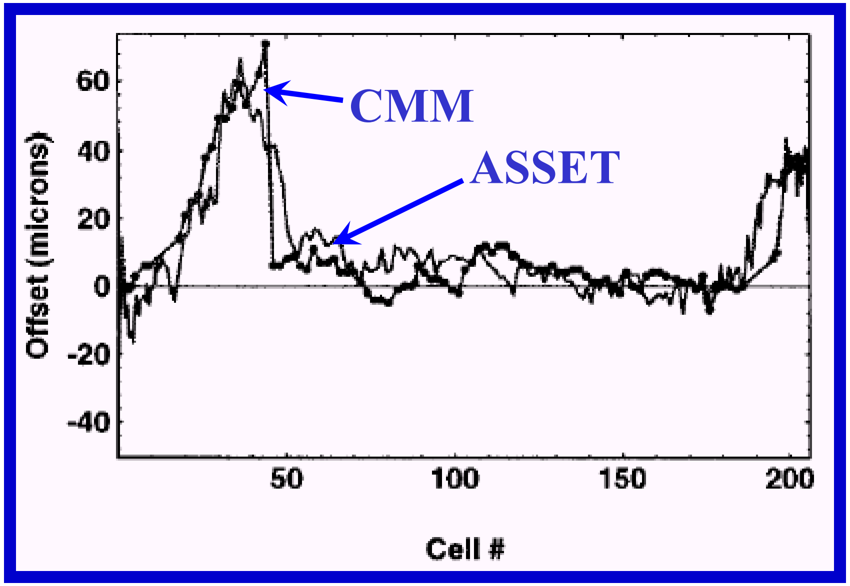
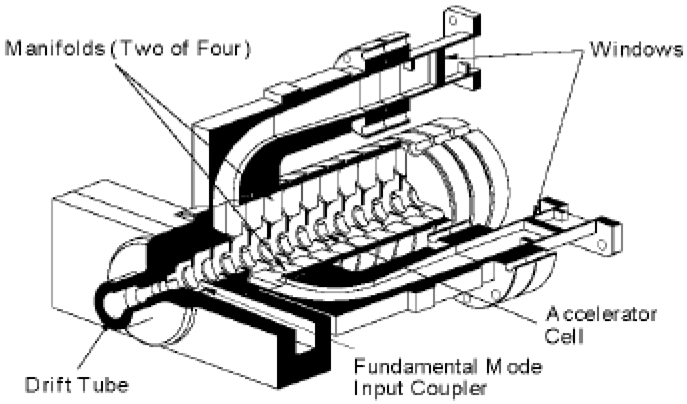


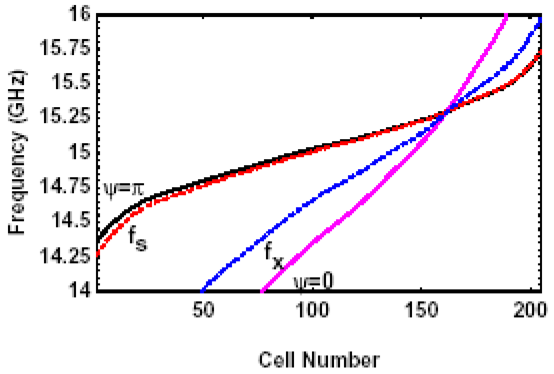
Illustration of the deviation of the synchronous frequency from the uncoupled one due to cell-to-cell detuning. The short horizontal lines indicate the extent to which cell offsets may be localized by frequency



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

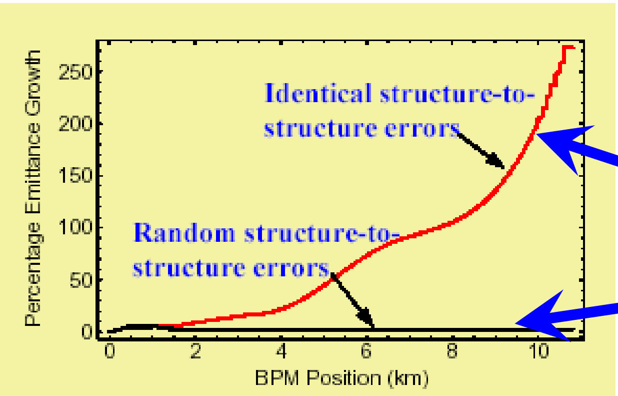
2.1 Summary of Manifold Suppression of Wakefields in Detuned Structures



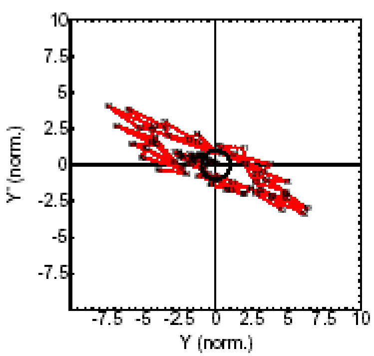


- The manifold is a single mode TE_{10} and it is cut off to the accelerating mode (thus there is little impact on the accelerating mode)
- Each manifold is tapered to maintain good coupling
- RDDS has circular manifolds (superior pumping compared to rectangular guide).
- From mechanical considerations 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.

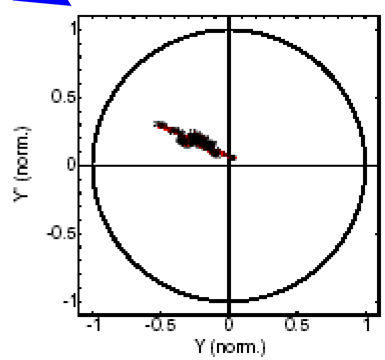
2.1 Beam Dynamics Simulations Under the Influence of Frequency Errors



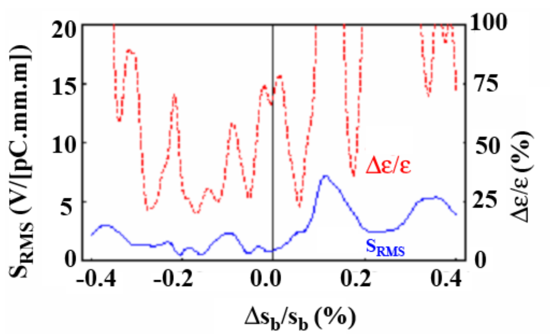
➢Emittance growth due to 3 MHz random frequency errors that are:
(a) reproduced from structure to structure,
(b) random from structure to structure.



➢y-y' phase space after beam progresses down 4720 structure with identical fabricagtion errors (3 MHz RMS)



➢y-y' phase space for non-identical fabrication errors from structure to structure



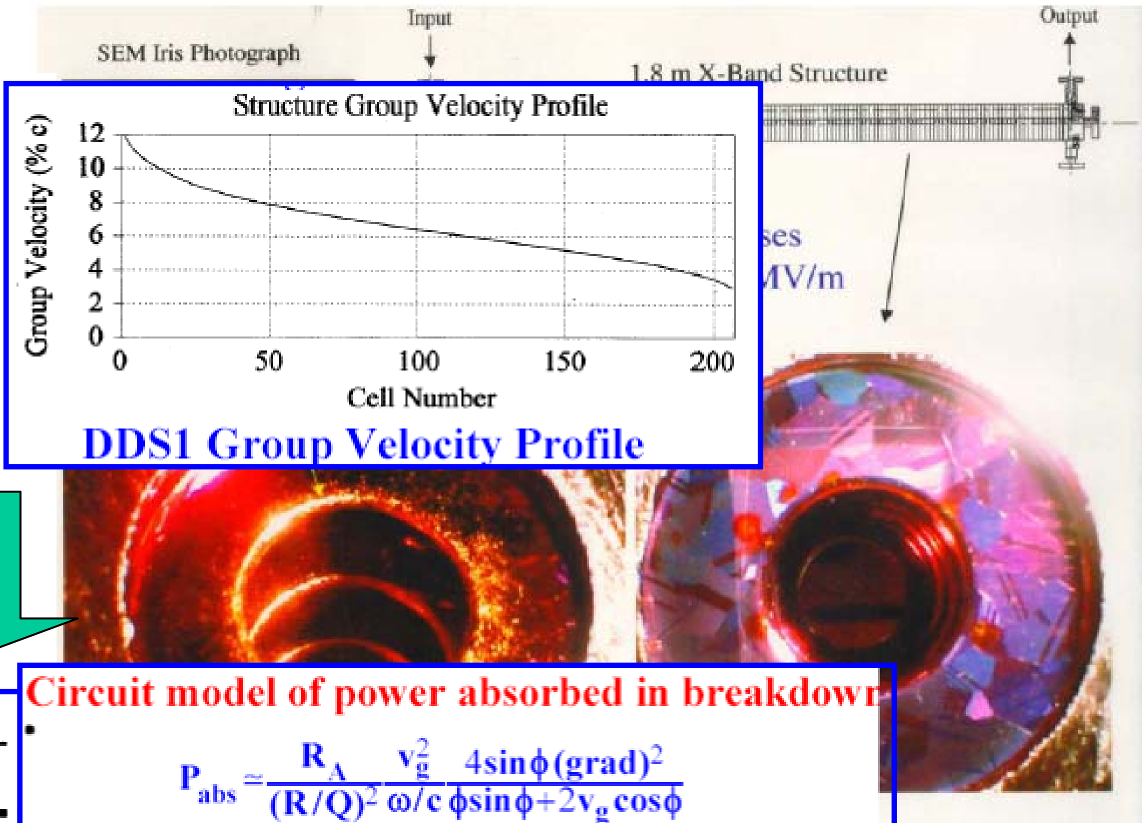
➢Increase random frequency errors to 20 MHz indicates the emittance is relatively insensitive to fabrication errors (larger than mode spacing!)
➢However, systematic errors define the stable region.

Ref: 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.

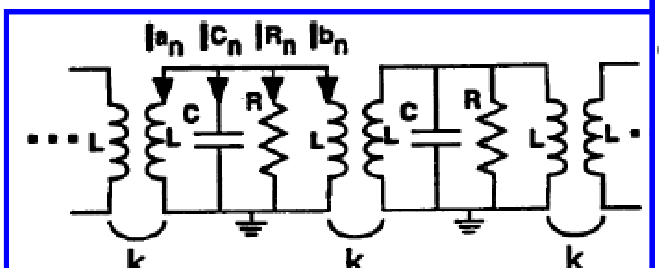
2.1 Effect of Breakdown Observed in DDS

- 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

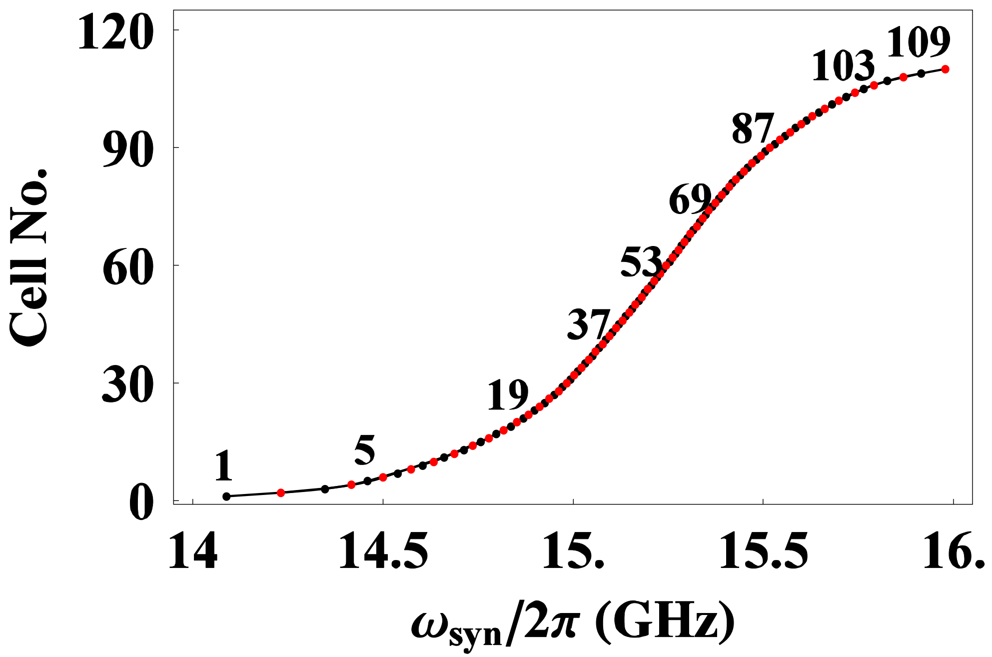


Circuit model of power absorbed in breakdown

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

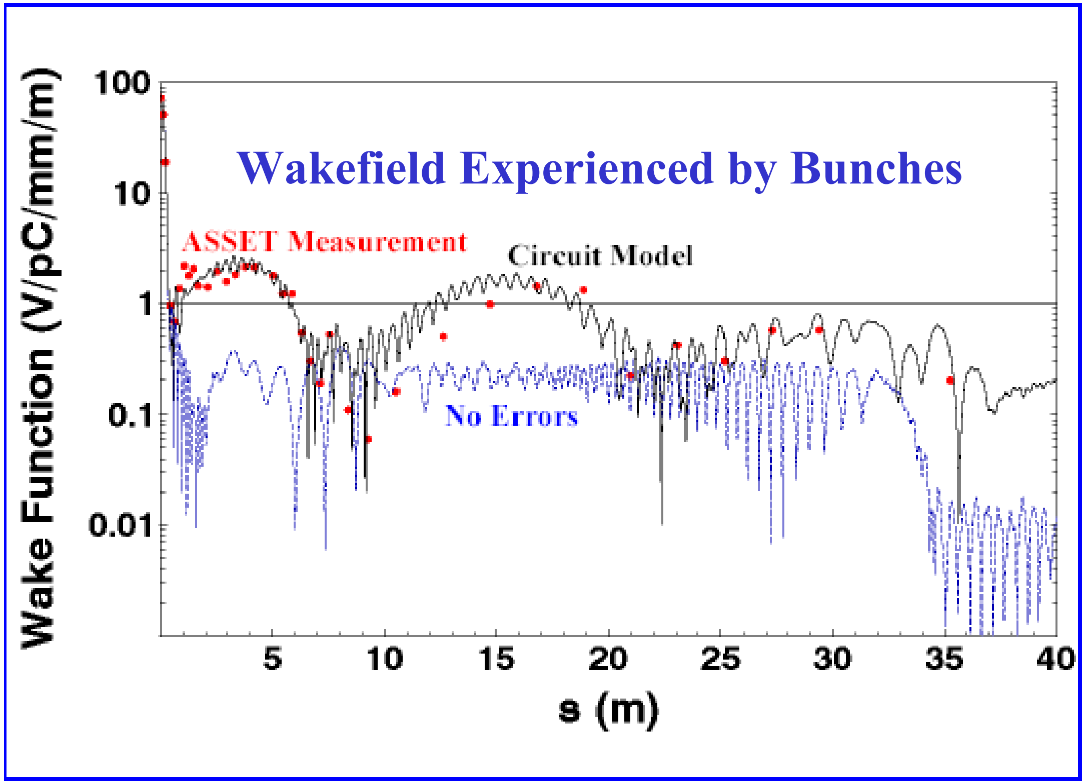
R_A resistance of breakdown, v_g is the group velocity, ϕ is the synchronous phase advance (=$2\pi/3$ for DDS1), grad the accelerating gradient, and R and Q are the shunt impedance and quality factor evaluated at the synchronous phase

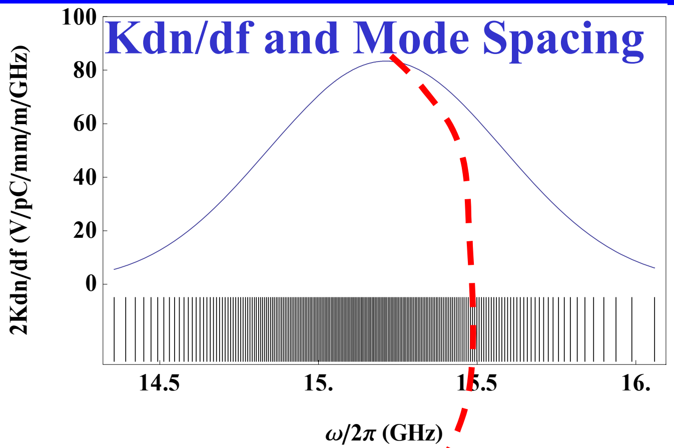
2.1 Interleaving of Cell Frequencies

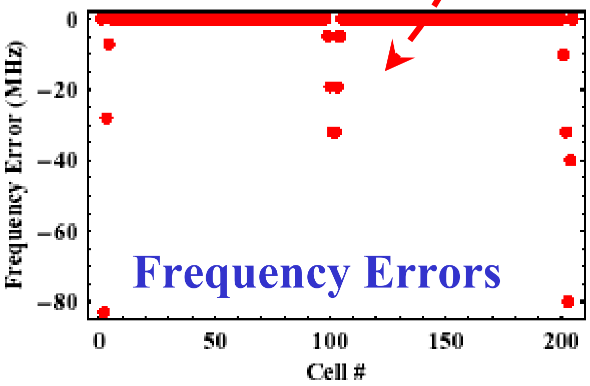


- Interleave dipole frequencies from successive structures
- The cells effectively sample the prescribed Gaussian distribution.
- We can fabricate structures such that neigbhouring structures are interleaved to reduce the magnitude of the re-coherence peak and to push it further out from the location of the first trailing bunch
- As there are a finite number of cells then eventually the modes add up constructively and the wake-field re-coheres at ($t \sim 1/f_{min}$).

2.1 Impact of Fabrication Errors on Wakefield Suppression in RDDS1







After diffusion bonding the 206 cells of RDDS1 an error was discovered in the first few and middle 6 cells due to the structure adhering to the ceramic supports at the ends and due to the stainless steel collar in the middle section which has a different expansion coefficient from the copper. The flaring gives rise to frequency errors of the order of 30MHz in the central cells. This effect has been cured by choosing a graphite supporting ring and by ensuring

2.1 Summary of NLC/GLC Wakefield Damping

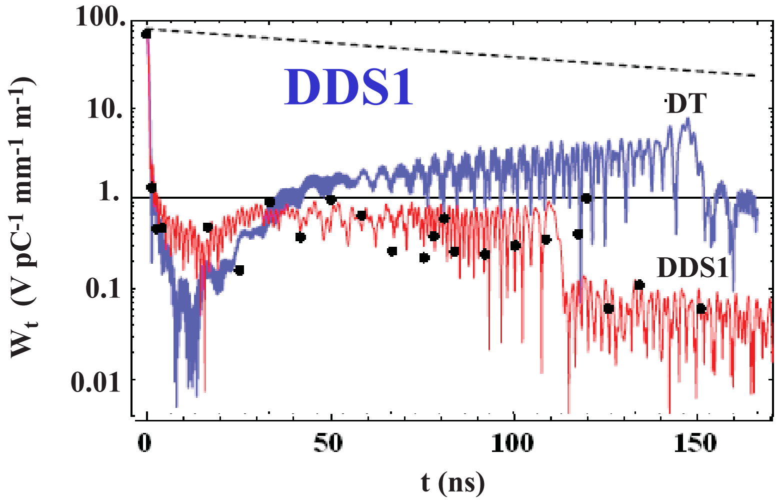
- **Detuning along with moderate damping has been shown to be well-predicted by the circuit model.**

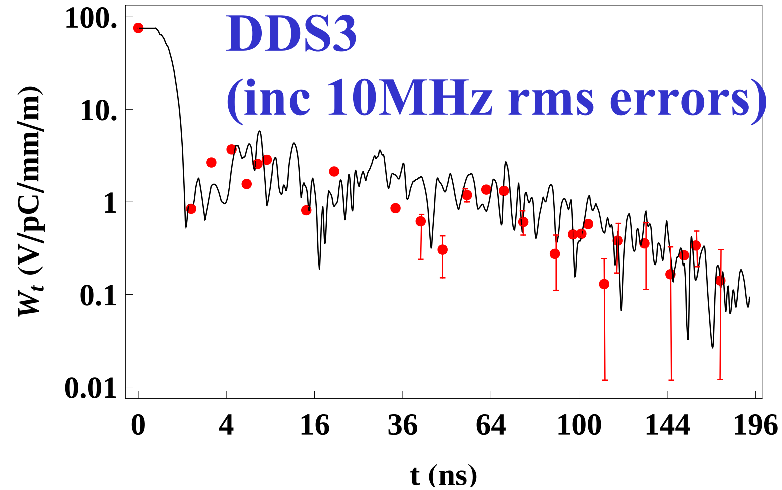
- **Interleaving of successive structures allows the detuning to be effective.**

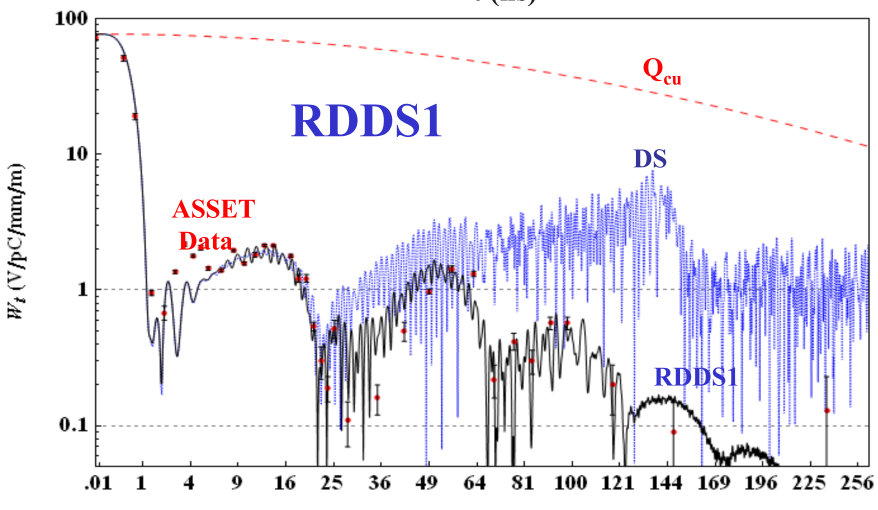
- **Manifold wakefield suppression has added benefits:**

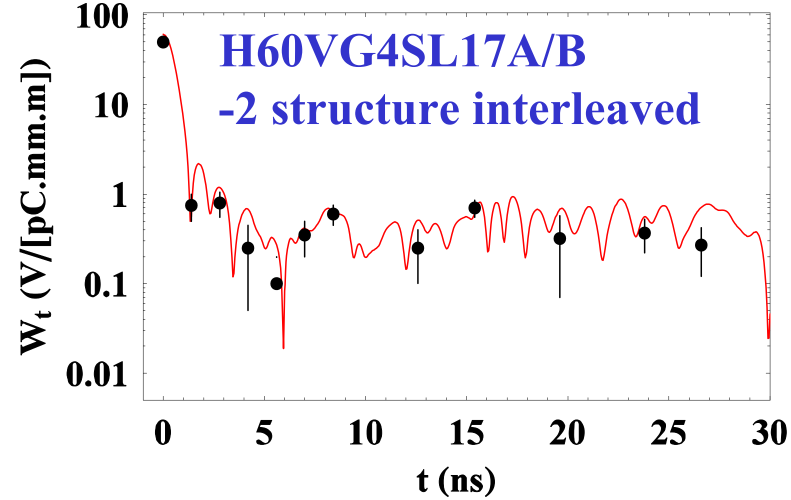
1. **Serves as built-in beam diagnostic**
2. **Allows internal alignment of cells to be obtained from manifold radiation**
3. **Serves as vacuum pump-outs.**

2.1 X-Band GLC/NLC Exp vs Cct Model

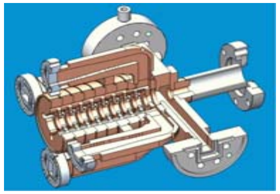






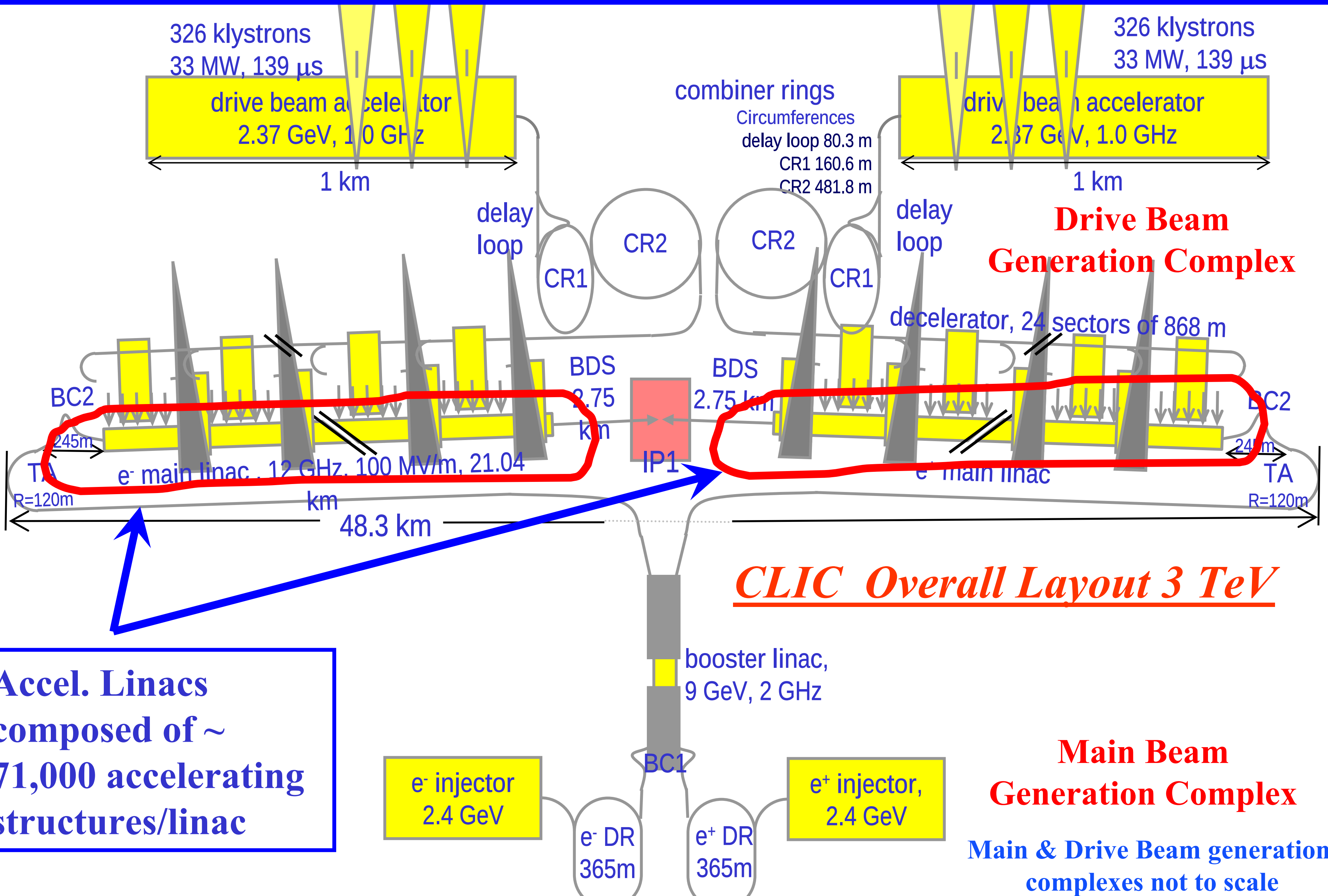


Conspectus of GLC/NLC Wake Function Prediction and Exp. Measurement (ASSET dots)



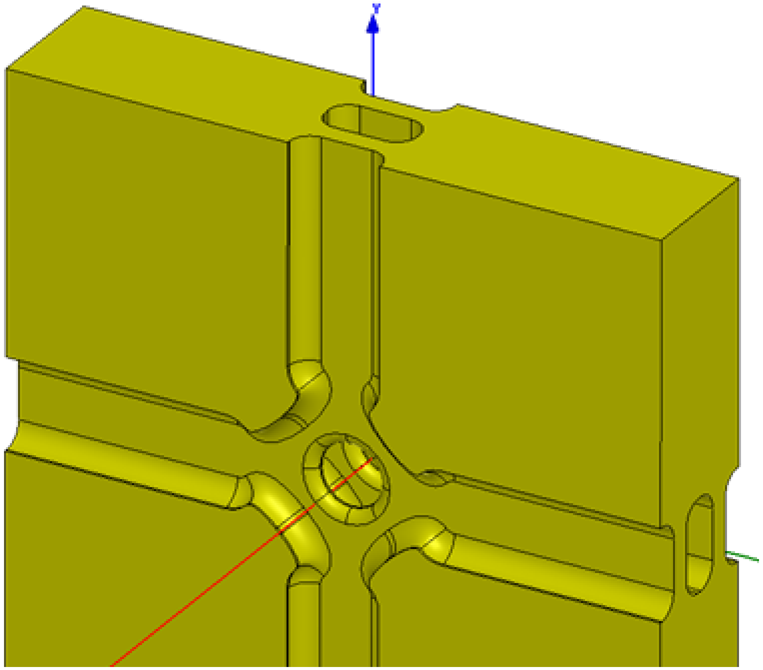
Refs: 1. R.M. Jones,et al, New J.Phys.11:033013,2009. 2. R.M. Jones et al., Phys.Rev.ST Accel. Beams 9:102001, 2006. 3. R.M. Jones, Phys.Rev.ST Accel. Beams, Oct.,2009.

2.2 X-Band HOM Suppression for CLIC

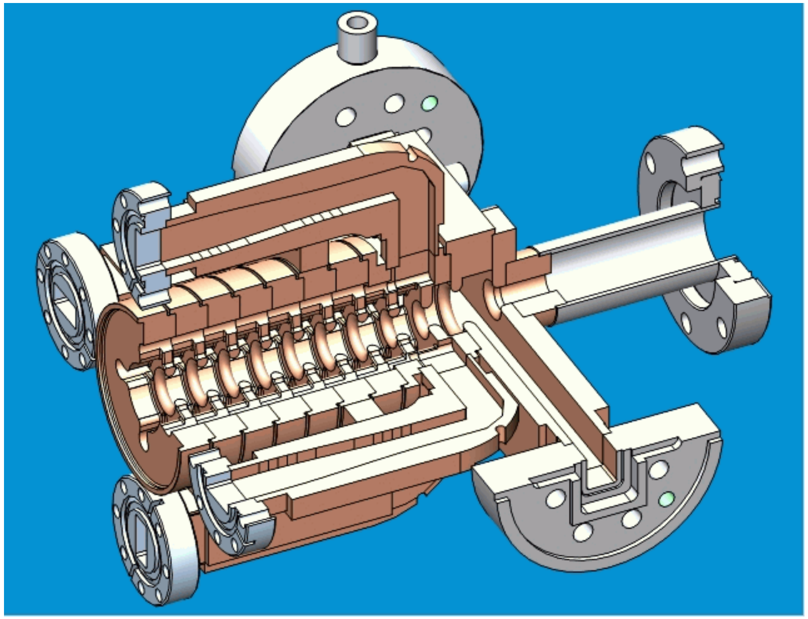


Accel. Linacs composed of ~ 71,000 accelerating structures/linac

2.2 X-Band HOM Suppression for CLIC



Current CLIC Baseline Design Heavily Damped Structure (Q ~ 10)



CAD of Conceptual Design for Alternate CLIC Moderately Damped Structure (Q ~ 500 - 1000)

2.2 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

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

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

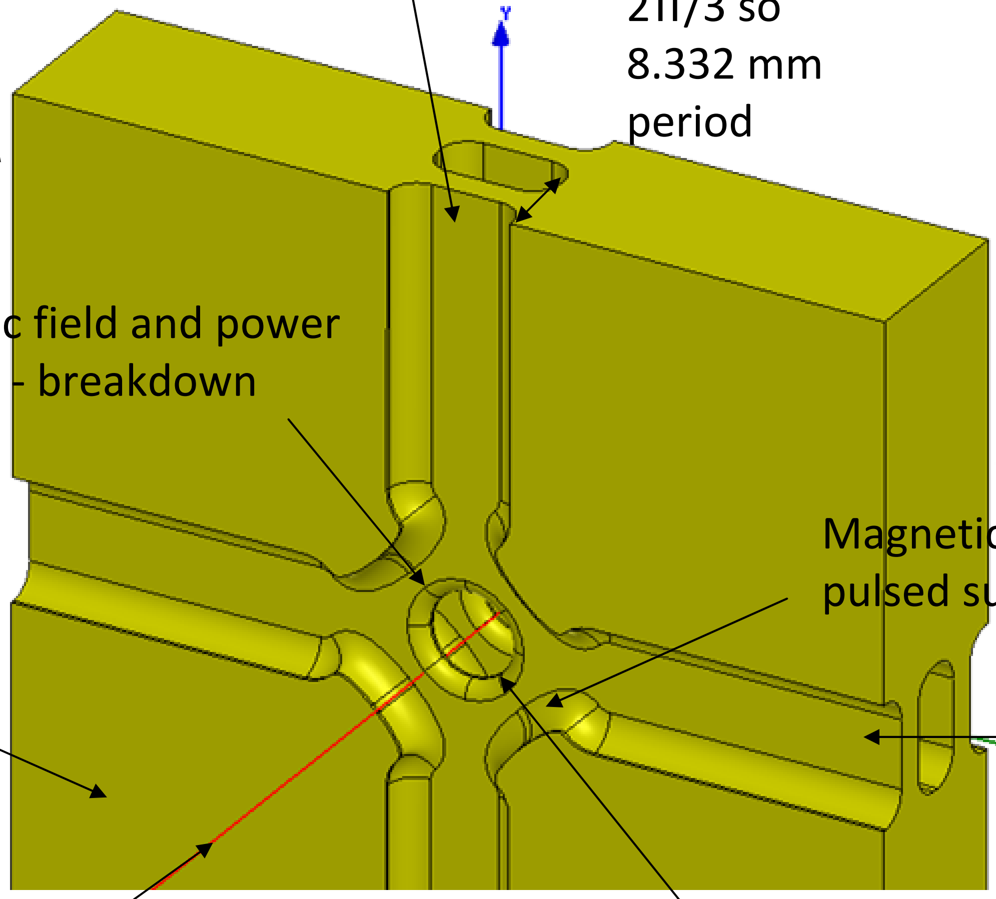
Ref: Grudiev and Wuensch, Design of an x-band accelerating structure for the CLIC main linacs, LINAC08

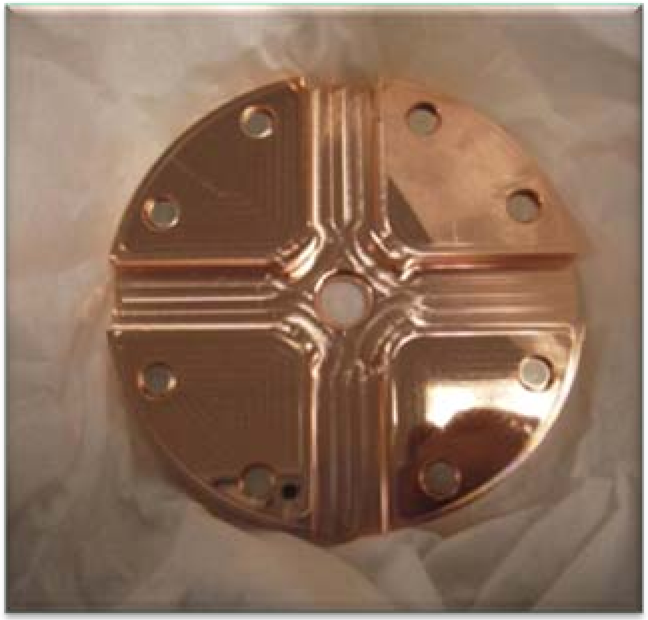
2.2 CLIC Baseline Parameters

Structure number	maxFoM	2(minCost)	4	6	CLIC_14Wu
RF phase advance per cell: $\Delta\varphi$ [°]	120	120	120	120	120
Average iris radius/wavelength: $<a>/\lambda$	0.115	0.105	0.115	0.125	0.12
Input/Output iris radii: $a_{1,2}$ [mm]	3.33, 2.4	2.85, 2.4	3.33, 2.4	3.84, 2.4	3.87, 2.13
Input/Output iris thickness: $d_{1,2}$ [mm]	3.33, 0.83	1.5, 0.83	1.83, 0.83	2.00, 0.83	2.66, 0.83
Group velocity: $v_g^{(1,2)}/c$ [%]	1.44, 1.0	1.28, 1.0	1.93, 1.0	2.93, 1.0	2.39, 0.65
N. of cells, structure length: N_c, l [mm]	12, 112	23, 204	25, 221	24, 212	24, 229
Bunch separation: N_s [rf cycles]	6	6	7	7	7
Number of bunches in a train: N_b	278	106	83	77	120
Pulse length, rise time: τ_p, τ_r [ns]	188.2, 17.3	126.9, 17.7	115.1, 17.3	101.5, 17.6	160, 30
Input power: P_{in} [MW], $P/C_{1,2}$ [GW/m]	54, 2.6, 2.4	61, 3.4, 2.6	73, 3.5, 2.7	87, 3.6	76, 3.1, 2.7
Max. surface field: E_{surf}^{max} [MV/m]	262	274	277	323	323
Max. temperature rise: ΔT^{max} [K]	55	30	23 (const)	30	37
Efficiency: η [%]	25.9	19.0	18.4	19.3	21.5
Luminosity per bunch X-ing: $L_{b\times}$ [m^{-2}]	2.4×10^{34}	2.0×10^{34}	2.4×10^{34}	2.8×10^{34}	2.6×10^{34}
Bunch population: N	5.3×10^{9}	4.2×10^{9}	5.3×10^{9}	6.5×10^{9}	5.8×10^{9}
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	11.6	8.8	8.3	8.3	9.5

Earlier set , Subsequently updated
Alexej Grudiev (*CERN*)

2.2 CLIC Baseline Accelerating Structure

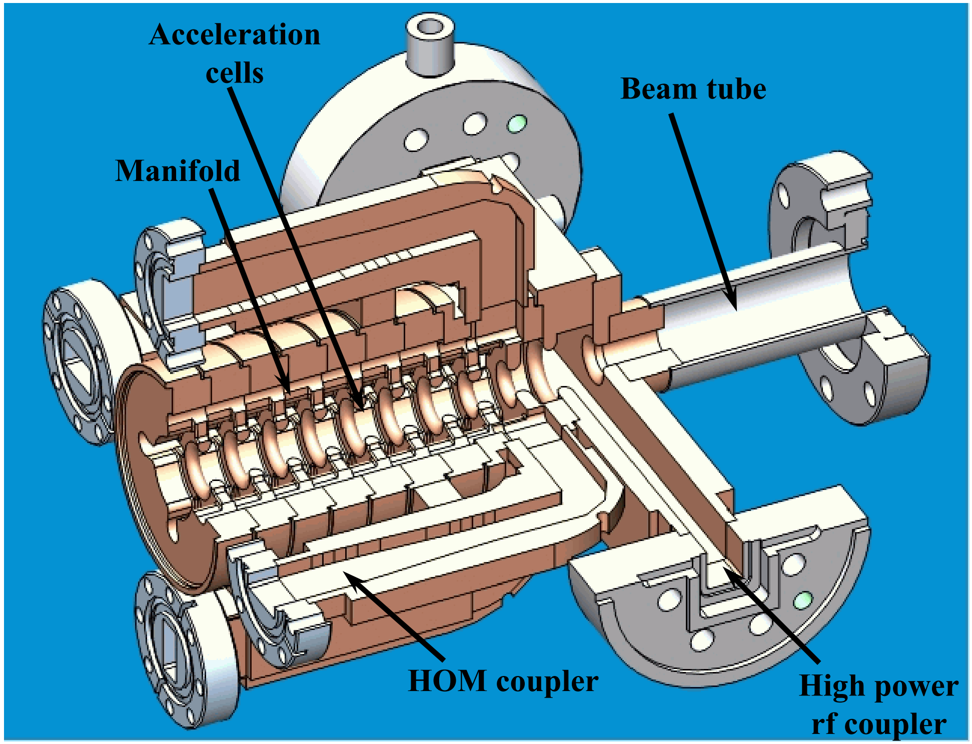




Heavy Damping, Q~10.
Dielectric materials impinge into structure

W. Wuensch, CERN

2.2 Alternate Design CLIC_DDS



- RDDS structure illustrates the essential features of the conceptual design
- Each of the cells is tapered –iris reduces with an Erf-like distribution
- HOM manifold running alongside main structure remove dipole radiation and damp 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

2.2 Initial CLIC_DDS Designs

Three designs

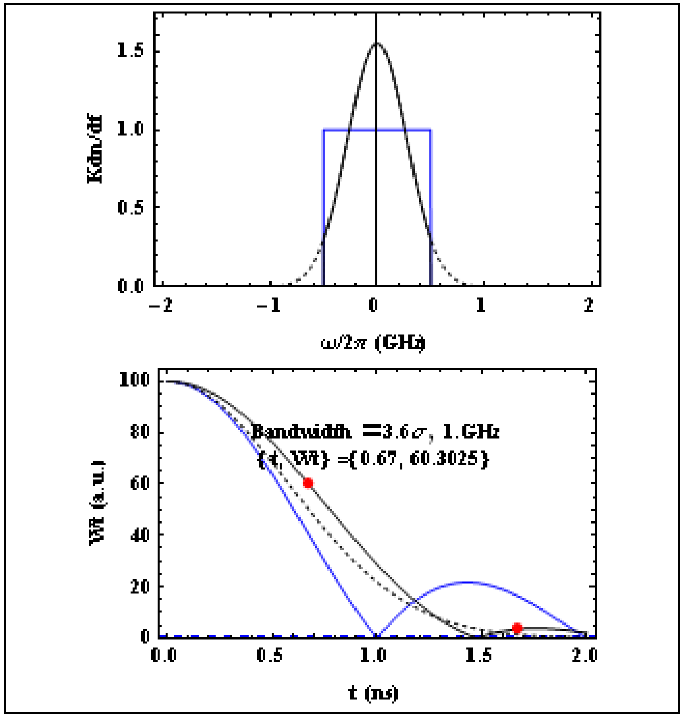
1. **Initial investigation of required bandwidth to damp all bunches (~3GHz)**

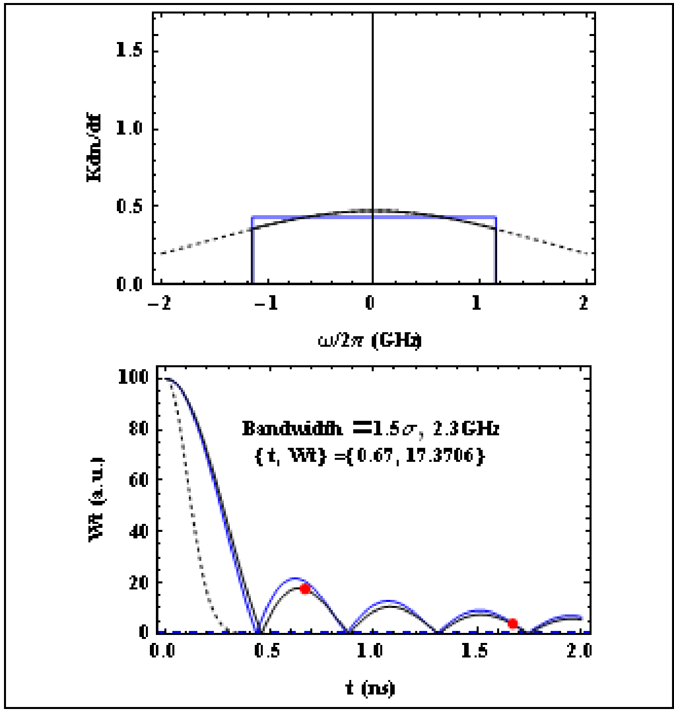
2. **Design, closely tied to CLIC_G, necessitates a bandwidth of ~ 1 GHz. Geometry modified to hit bunch zero crossings in the wakefield .**

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 ~ 2.3 GHz ~ 3.6σ, 13.75%).**

2.2 Initial CLIC_DDS Design –Δf?

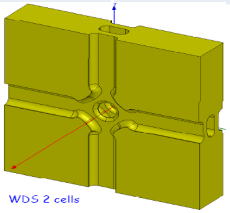
Structure	CLIC _G
Frequency (GHz)	12
Avg. Iris radius/wavelength <a>/λ	0.11
Input / Output iris radii (mm)	3.15, 2.35
Input / Output iris thickness (mm)	1.67, 1.0
Group velocity (% c)	1.66, 0.83
No. of cells per cavity	24
Bunch separation (rf cycles)	6
No. of bunches in a train	312





Lowest dipole
Δf ~ 1GHz
Q~ 10

CLIC_G



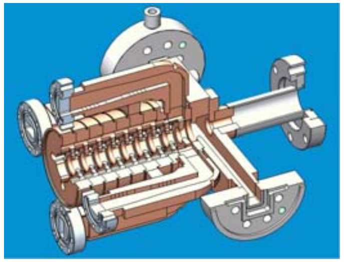
Bandwidth Variation

Truncated Gaussian :

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

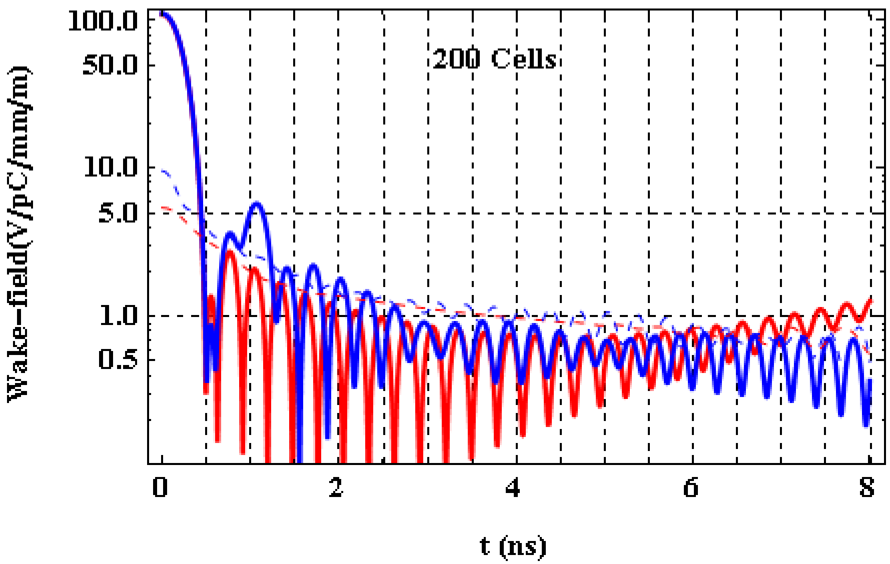
$$\text{where}: \chi(t,\Delta f) = \frac{\mathrm{Re}\left\{\mathrm{erf}\left(\left[n_\sigma - 4i\pi\sigma t\right]/2\sqrt{2}\right)\right\}}{\mathrm{erf}\left(n_\sigma/2\sqrt{2}\right)}$$

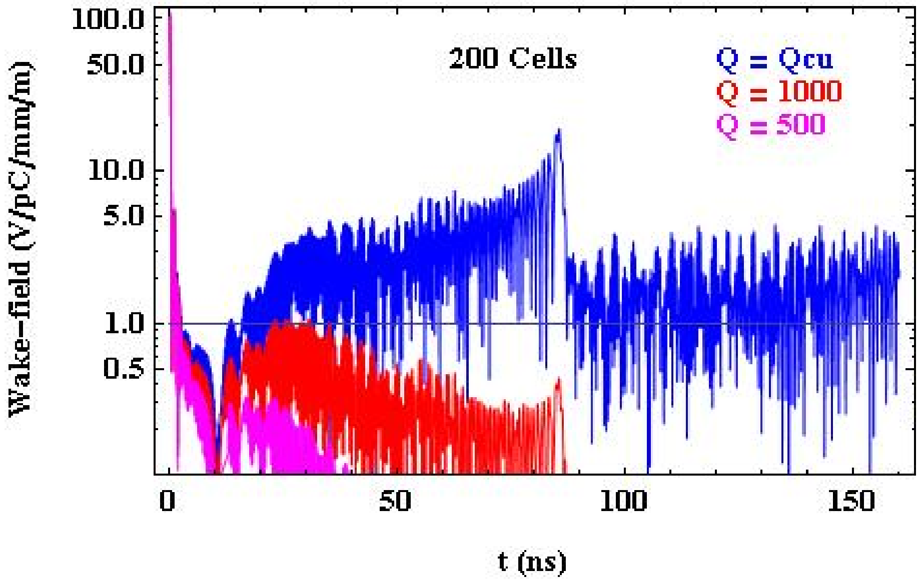
σ Variation



⇒ **CLIC_DDS Uncoupled Design**

2.2 Initial design for CLIC DDS



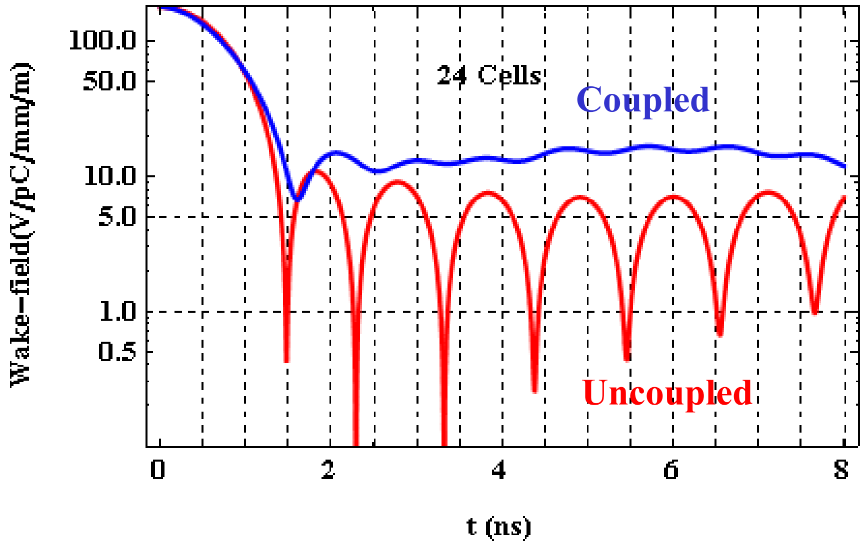


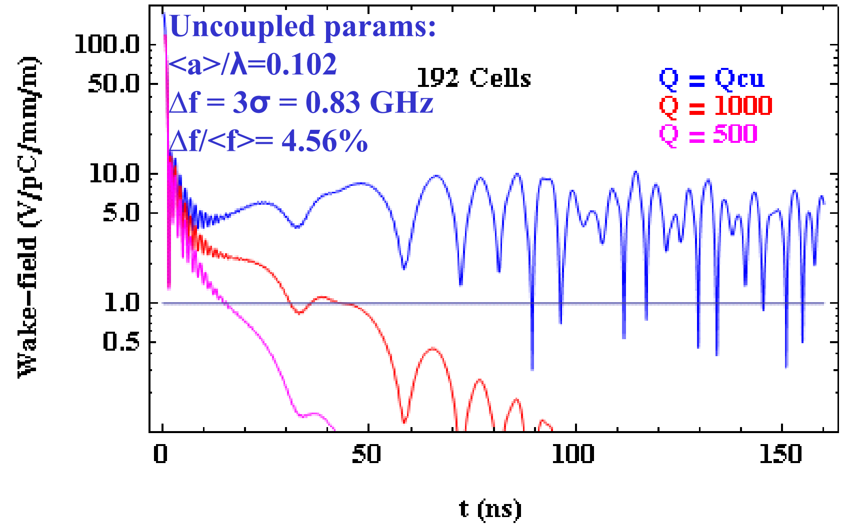
First dipole Uncoupled, coupled.
Dashed curves: second dipole

- **8-fold interleaving employed**
- **Finite no of modes leads to a recoherance at ~ 85 ns.**
- **For a moderate damping Q imposed of ~1000, amplitude of wake is still below 1V/pc/mm/m**

- **3.3 GHz structure does satisfy the beam dynamics constraints**
- **However, it fails to satisfy RF breakdown constraints as surface fields are unacceptable.**

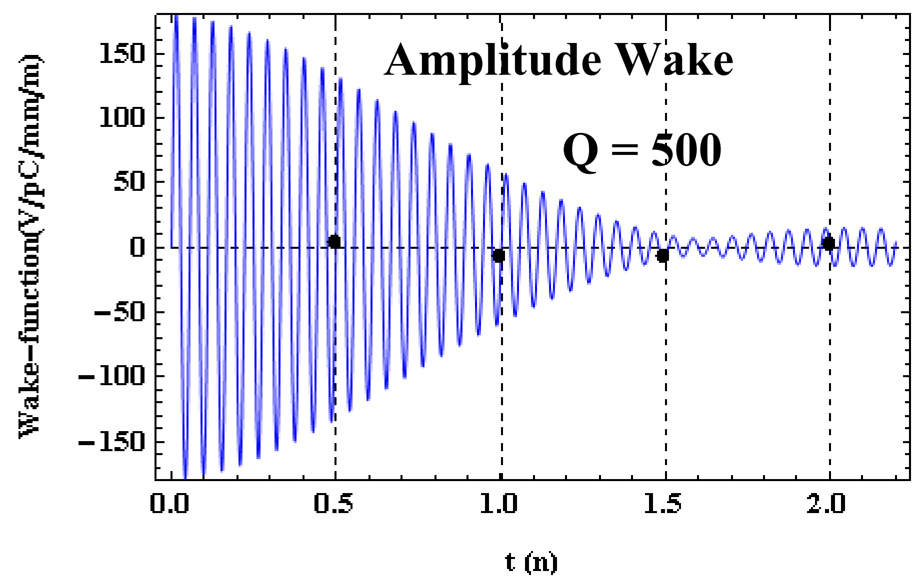
2.2 Gaussian linked to CLIC_G parameters –Zero Crossings



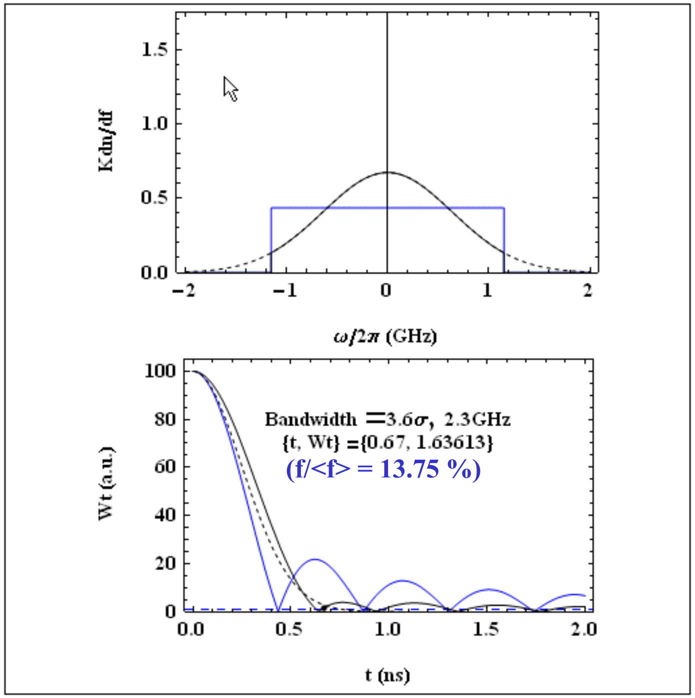


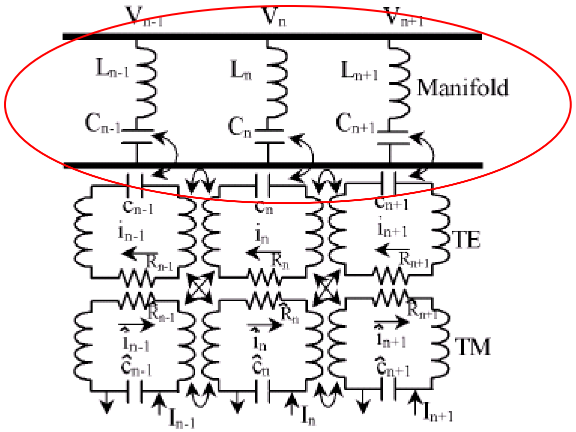
➢Systematically shift cell parameters (aperture and cavity radius) in order to position bunches at the zero crossing in the amplitude of the wake function.

➢Efficacy of the method requires a suite of simulations in order to determine the manufacturing tolerances.



2.2 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

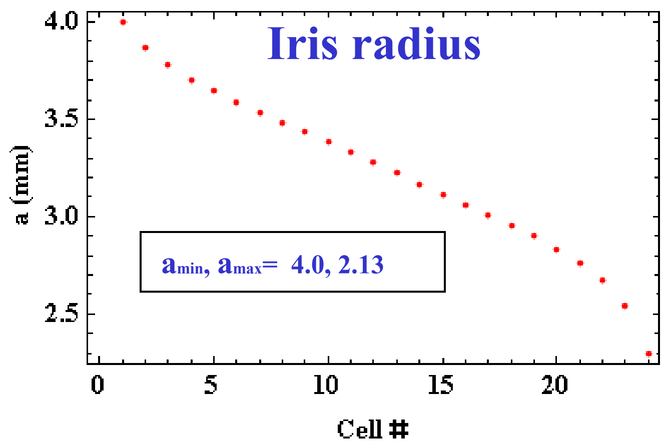
Cell 24

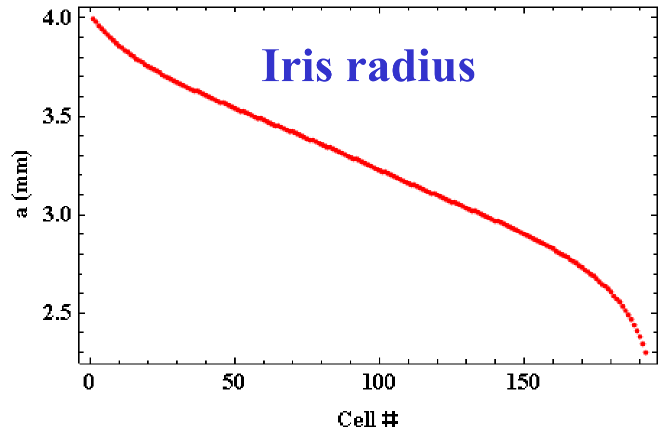
- Iris radius = 2.13 mm
- Iris thickness = 0.7 mm,
- ellipticity = 2
- Q = 6355
- R'/Q = 20,090 Ω/m
- vg/c = 0.9 %c

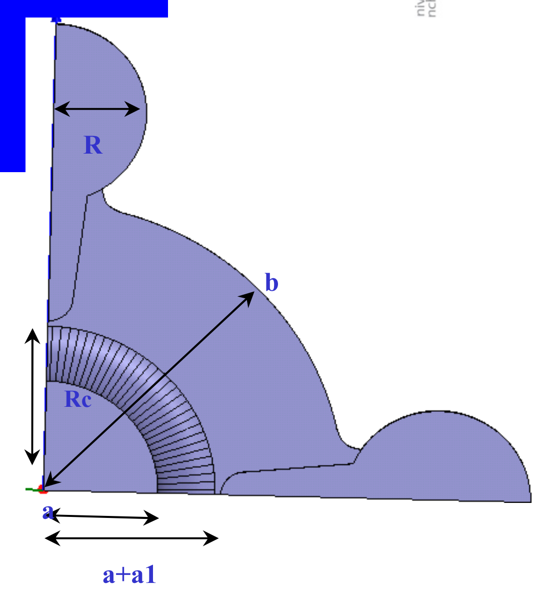
Cct Model Including Manifold-Coupling

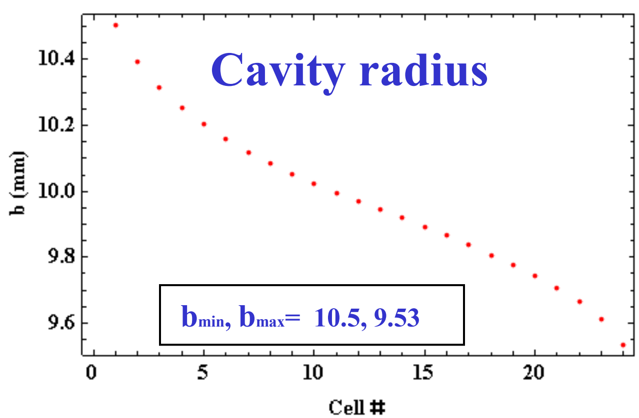
➢ Employed spectral function and cct model, including Manifold-Coupling, to calculate overall wakefunction.

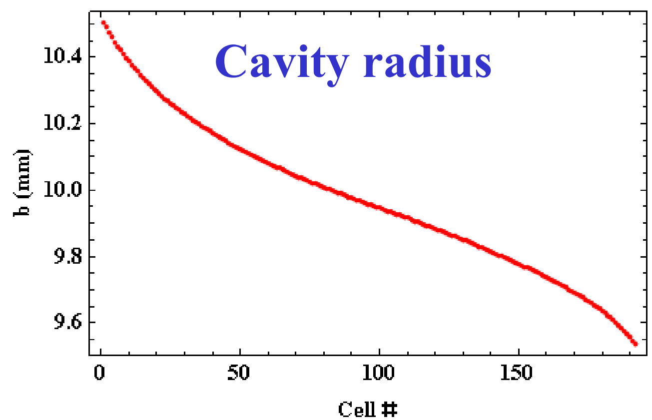
2.2 Structure Geometry: Cell Parameters

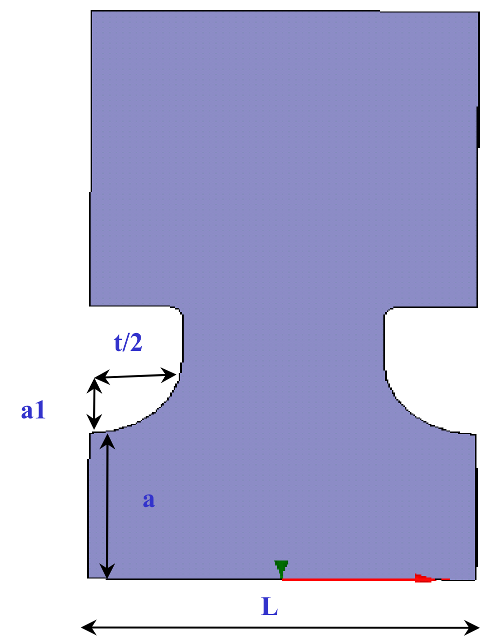










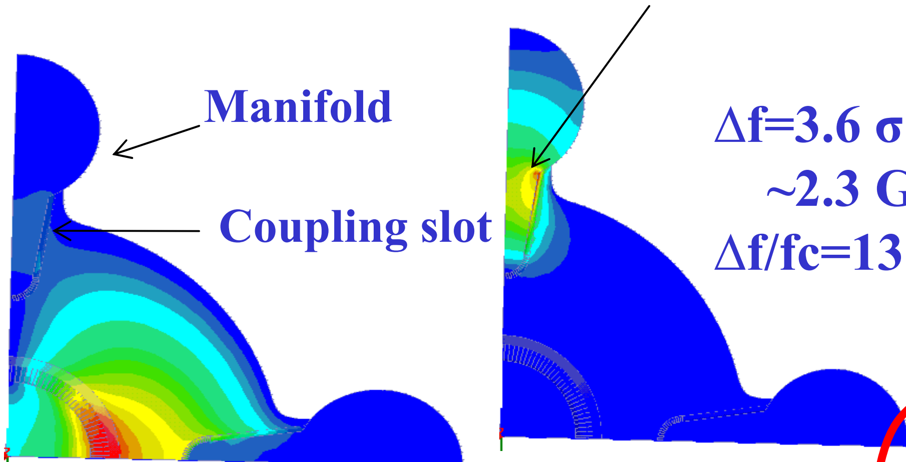


Sparse Sampled HPT (High Power Test)

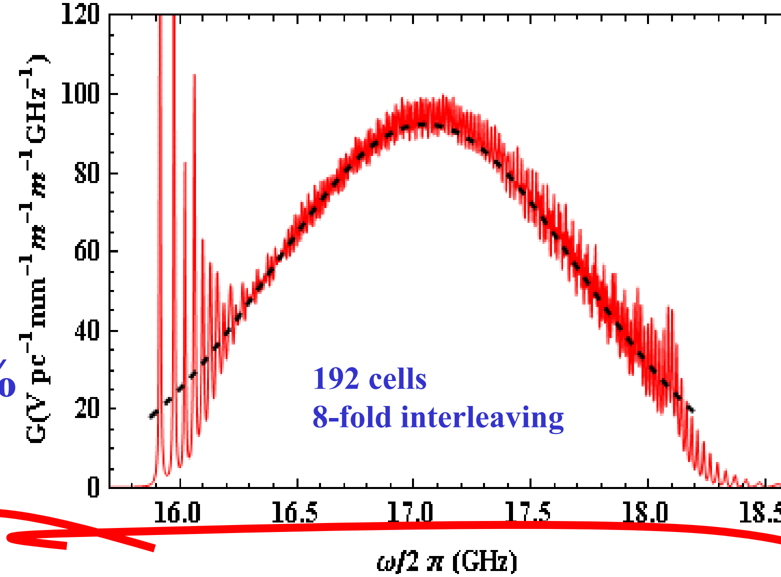
Fully Interleaved 8-structures

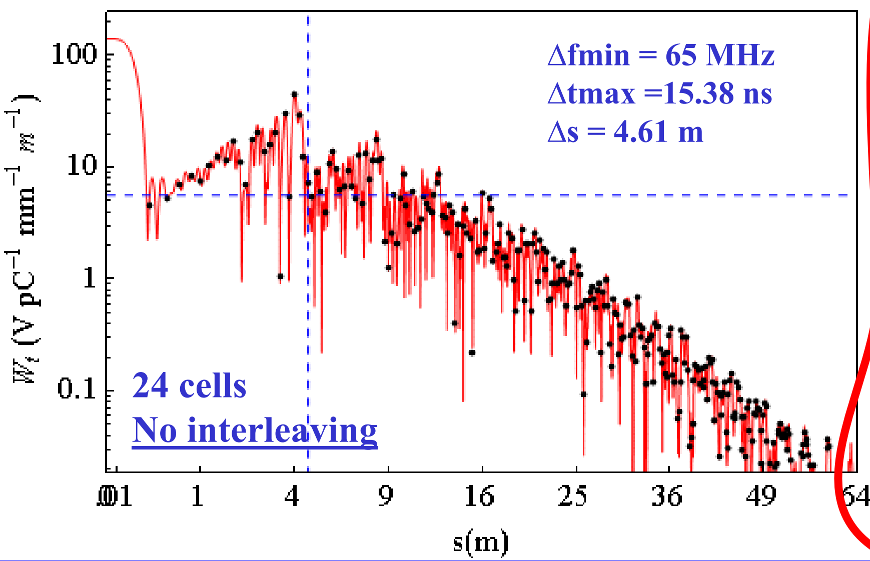
2.2 Summary of CLIC_DDS_C

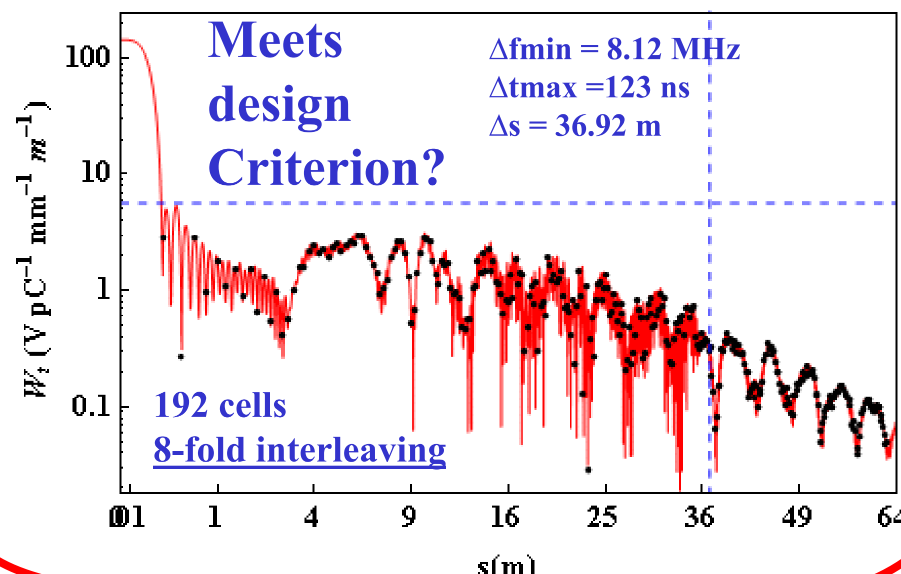
Dipole mode **Manifold mode**



Δf=3.6 σ
~2.3 GHz
Δf/fc=13.75%





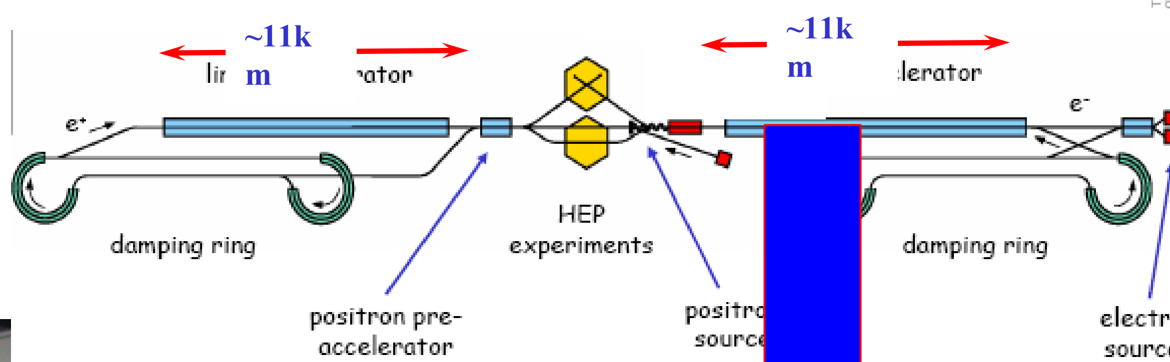


- **Structure being fabricated at CERN.**
- **ETA Dec 2010?**

3. HOMs in SCRF Cavities

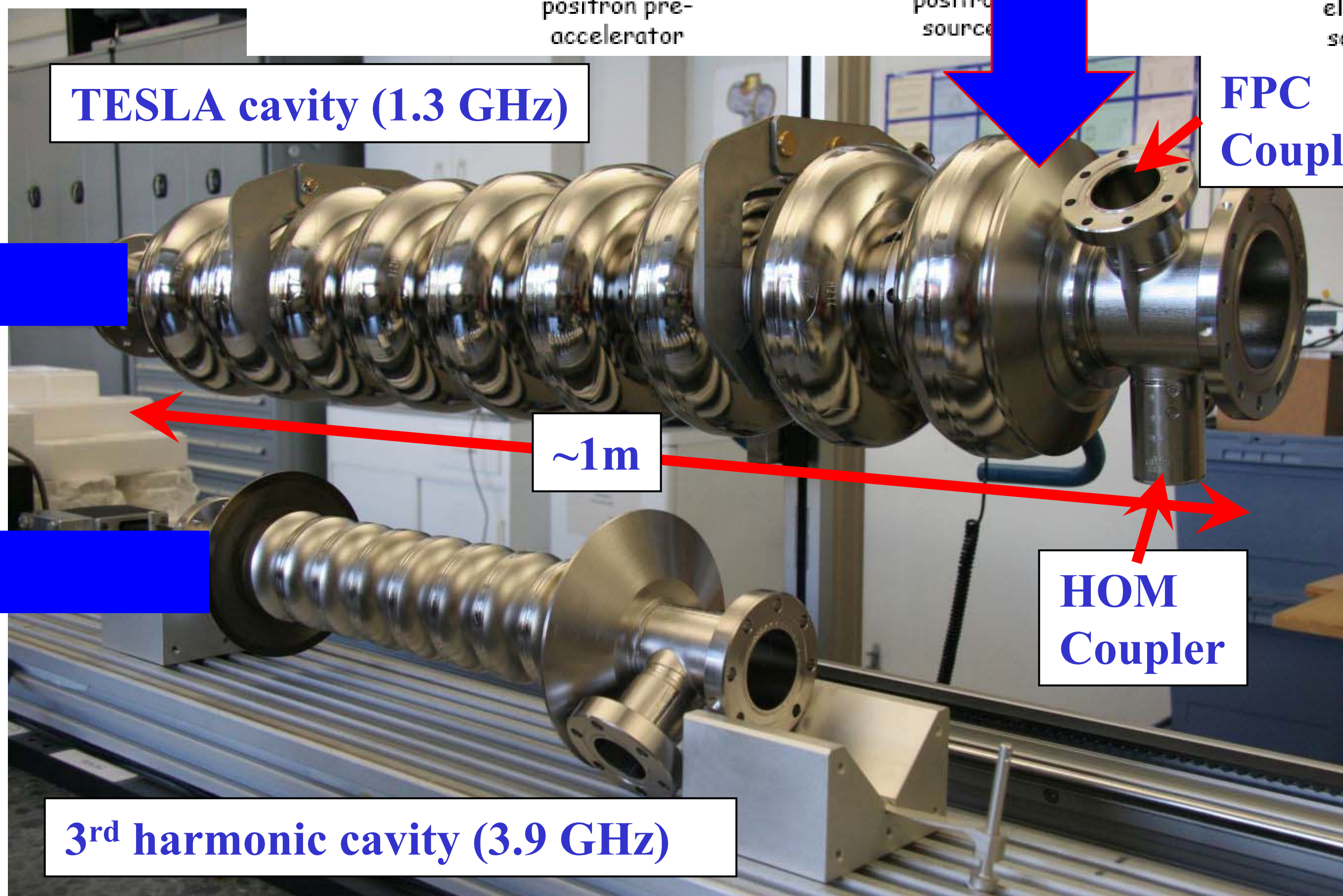
Schematic of International Linear Collider (ILC)

http://www.linearcollider.org



Used at XFEL and FLASH. Baseline design for main accelerators in ILC.

Used at XFEL and FLASH in order to flatten the field profile and reduce energy spread.

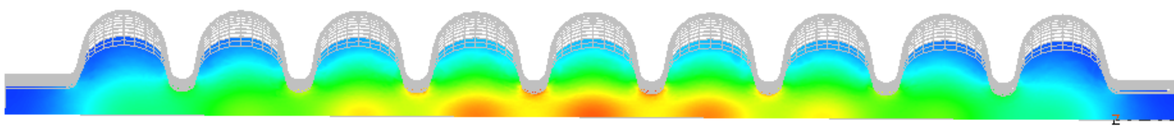


3. HOMs in SCRF ILC Cavities

Modal expansive of wake seen by beam traversing ~ 20,000 cavities:

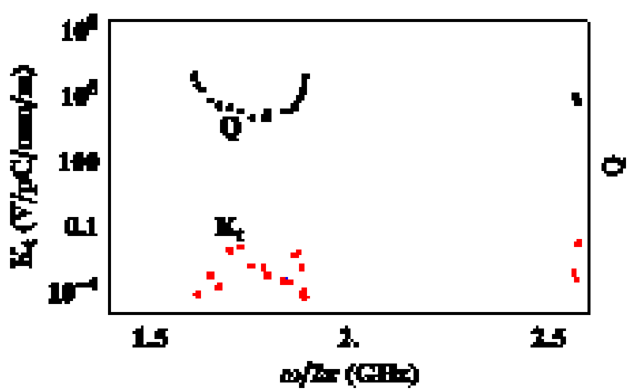
$$W(s) = 2\mathrm{Re}\left\{\sum_{n=1}^{N} K_n e^{i\omega_n s/c} e^{-\omega_n s/2Q_n c}\right\} U(s)$$

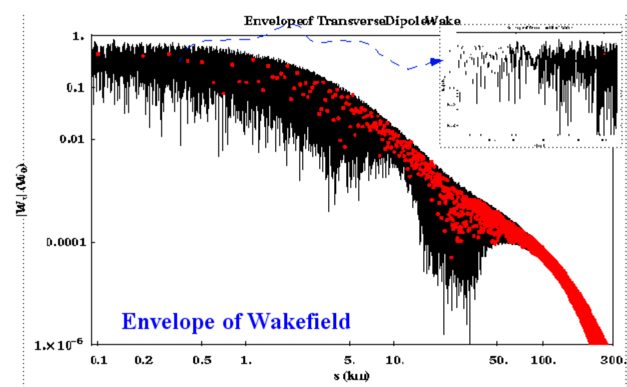
Where N is the number of modes, U(t) is the unit step function, the nth mode has a quality factor of Q_n, a kick factor $K_n = \left|\int_0^L E_z(s) e^{i\omega_n s/c} ds\right|^2 / 4U_n$ **(E_z = axial E-field and U_n =energy stored in mode n) and a synchronous frequency $\omega_n/2\pi$.**



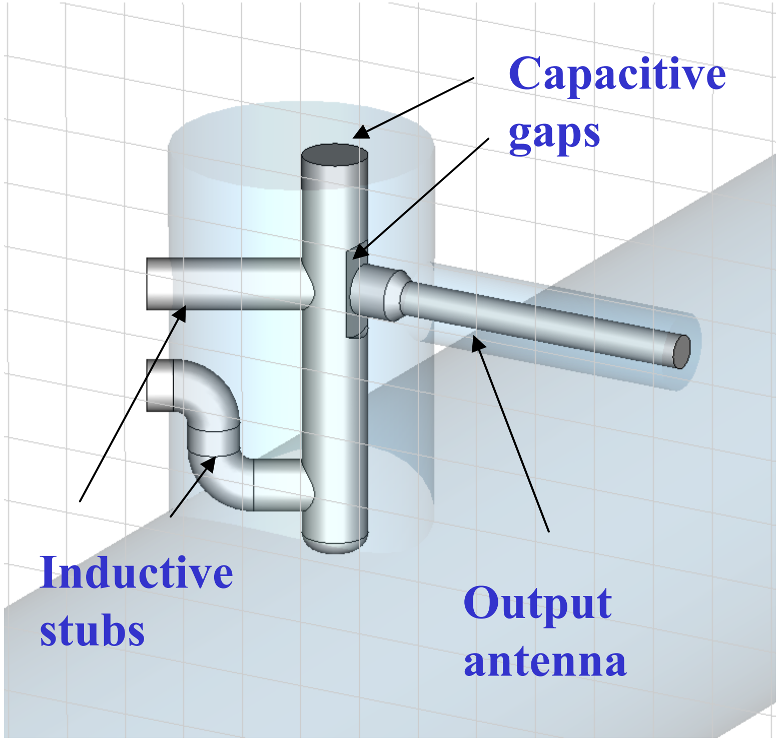
Dipole field in 9-cell TESLA-style cavity computed with HFSS

- **Calculate Ks, kick factors and ωn/2π , eigenfreqs for lower (~ 3 bands) with HFFS**
- **Measure Qs for lower bands ('cold' measurement).**
- **Sum modes to obtain wakefield.**





3. HOMs in SCRF Cavities

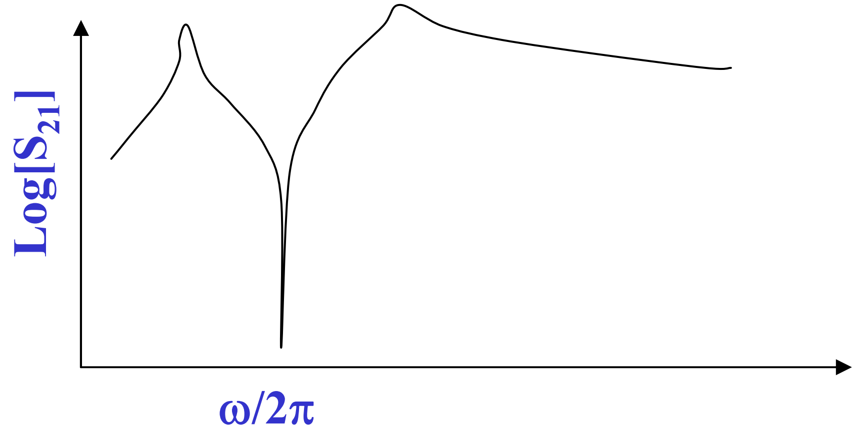


•F-probe couplers are a type of co-axial coupler, commonly used to damp HOM's in superconducting cavities.

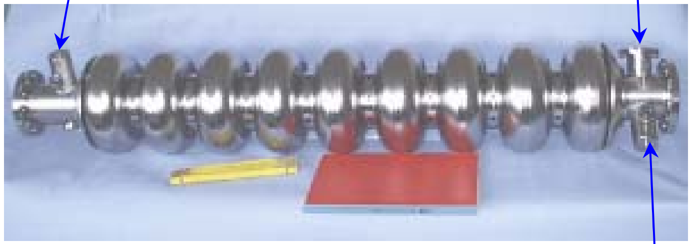
•These complex shapes are designed to provide the coupler with additional capacitances and inductances.

•These additional capacitances and inductances form resonances which preferentially couple at specific frequencies.

The LCR circuit can be used to reduce coupling to the operating mode (which we do not wish to damp) or to increase coupling at dangerous HOMs.



3. Cross-Coupled HOMs in ILC Linacs



$V_y = iV_x(0) \sin 2\theta \exp(i<\omega>t) \sin(\Delta\omega t/2)$

Thus for $\theta = 0$ or $\pi/2$ $V_y(0) = 0$ as expected!

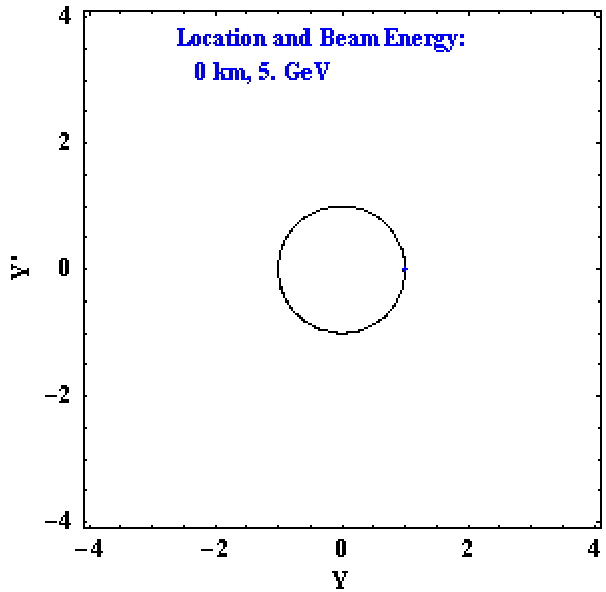
The additional kick to the beam is of the form:

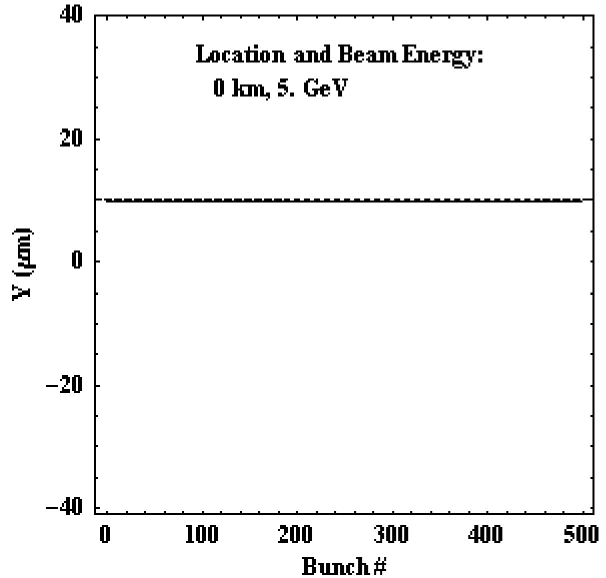
$$V(t)= \Sigma K_n \sin(\omega_p t) \exp(-\omega_{pt}/2Q_p)U(t)y + \Sigma K_n \cos(<\omega_p>t) \sin(\Delta\omega_p t/2) \exp(-<\omega_{p>}t/2Q_p)U(t)x$$

Where the sum is taken over all modes of interest and U(t) is the unit step function

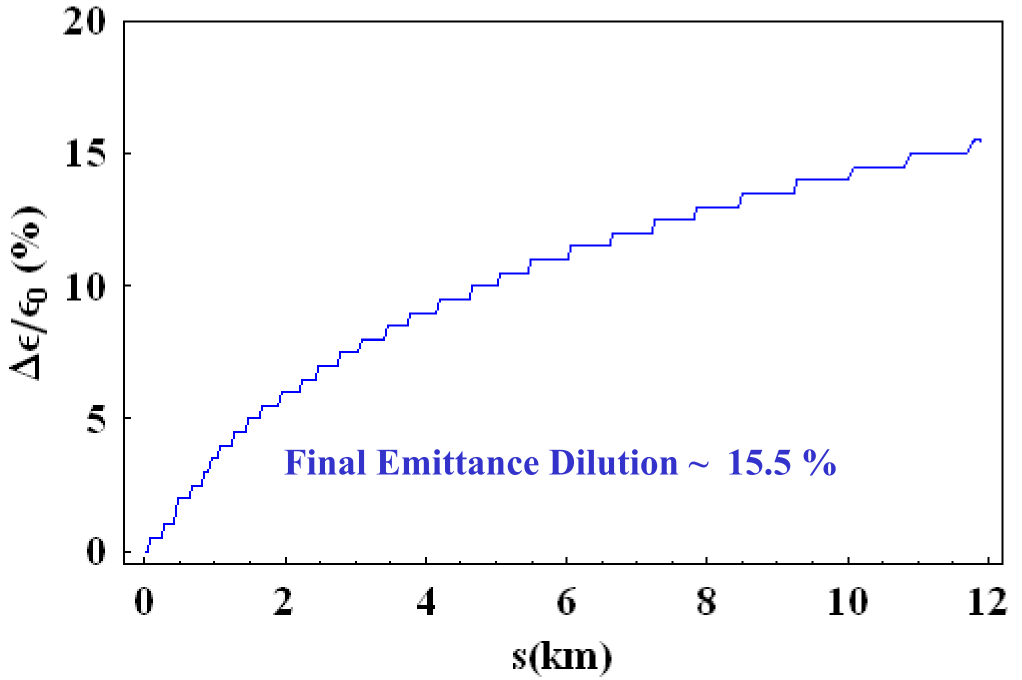
=> Recent TTF experiments (Frisch, Ross, Baboi, Gloch, Shinton, Jones, and Molloy) suggest that this frequency splitting varies by ~ 400 kHz to 800 kHz. In all simulations here we use 600 kHz frequency splitting for all modes.

3. Beam Dynamics of HOMs in ILC Linac



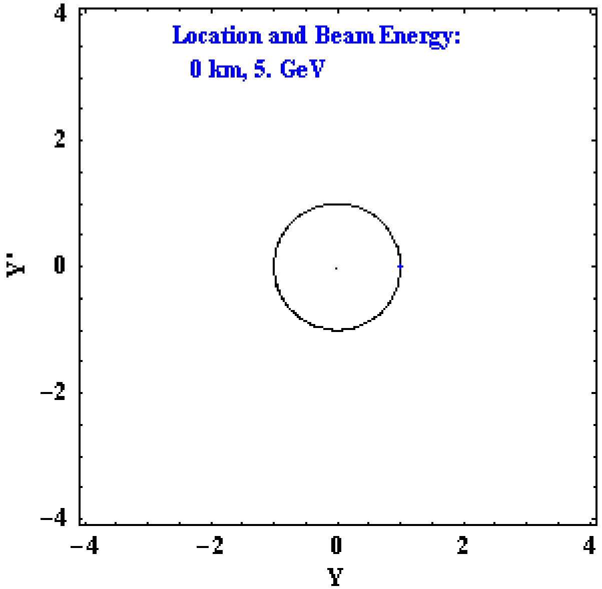


Emittance Dilution From Conventional Vertical Wakes => Xoffset =0

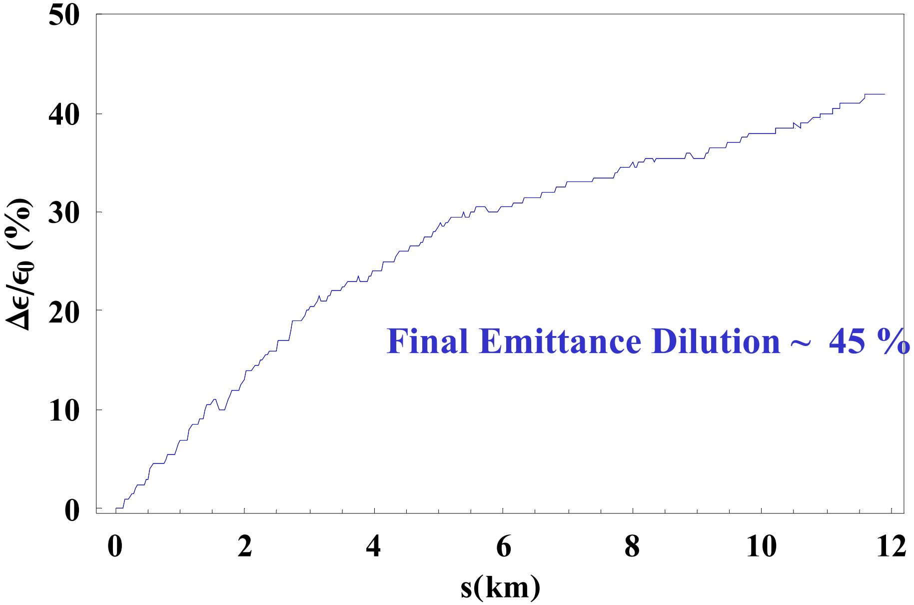


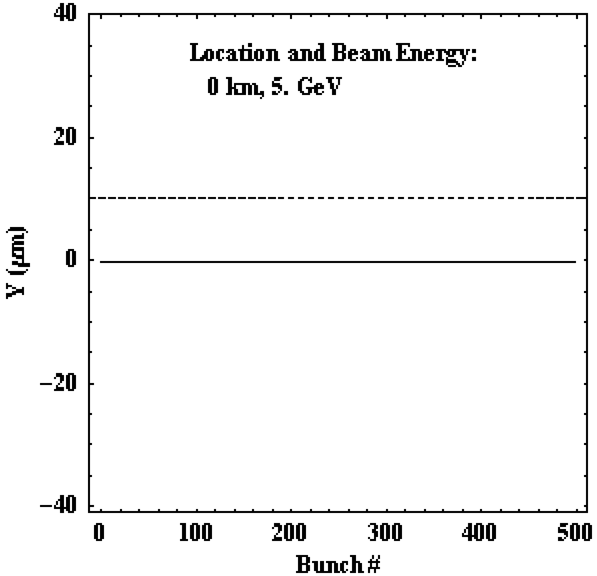
- 500 particles in all simulations.
- Initial vertical offset ~10 μm
- No Horizontal offset!
- (c.f. initial beam $\sigma_{y,x}$ ~ 10.1 μm, 270 μm)
- *Azimuthal phase fixed at π/4*
- Long + Short range wakes included in simulations

3. Cross-Coupled HOMs in ILC Linacs



Emittance Dilution From Cross-Coupling Wakes => Yoffset =0



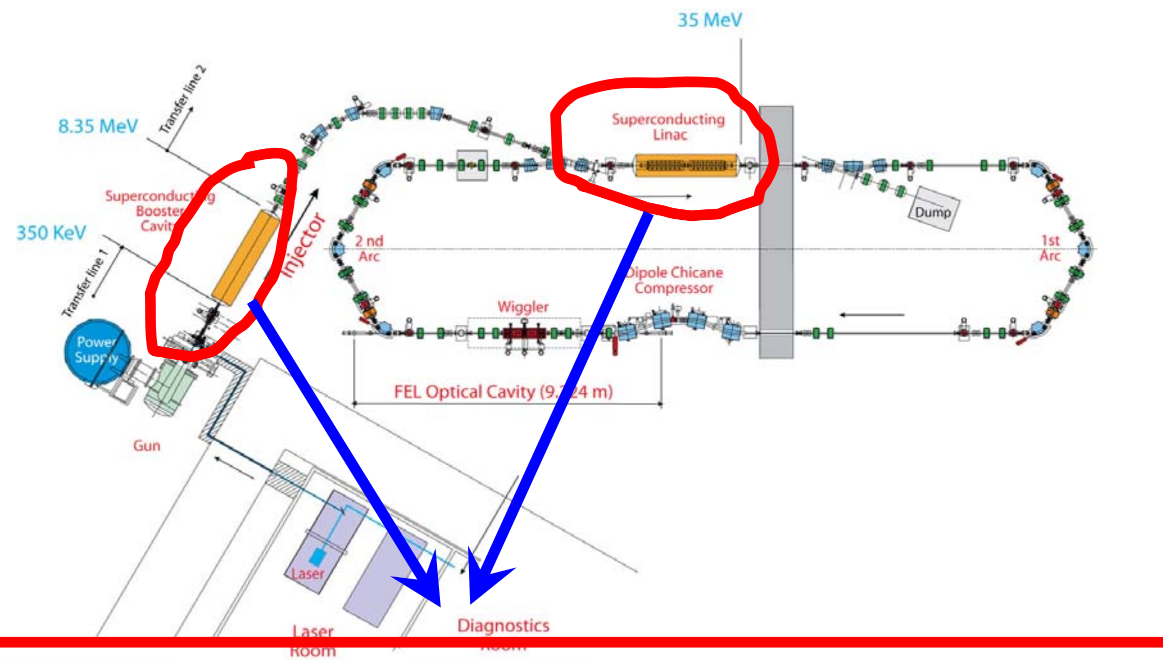


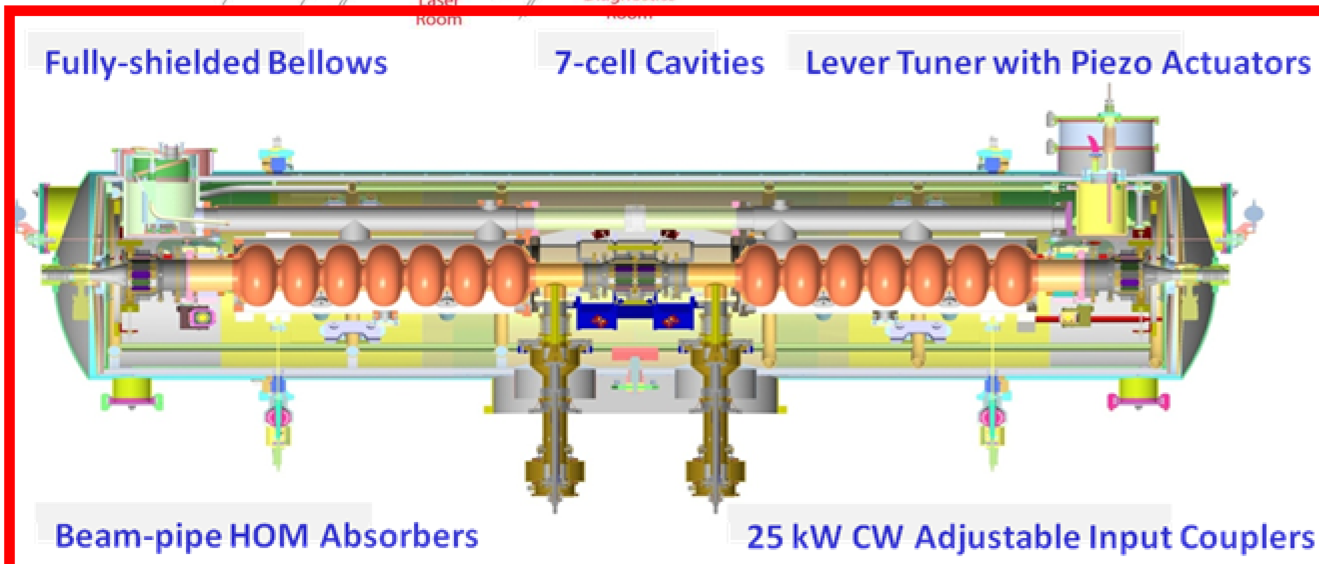
- 500 particles in all simulations.
- Initial horizonal offset ~400 μm
- No vertical offset!
- (c.f. initial beam $\sigma_{y,x}$ ~ 10.1 μm, 270 μm)
- *Azimuthal phase fixed at π/4*
- Long range wakes only included in simulations

4. HOMs in Energy Recovery Linacs

ALICE (Accelerators and Lasers In Combined Experiments)

- ALICE is a prototype accelerator, designed and built at Daresbury Laboratory.
- Formerly known as ERLP (Energy Recovery Linac Prototype).
- High quality electron bunches are produced from a photocathode
- Beam accelerated to 35 MeV.
- Bunches are compressed, to stimulate the production of intense, short pulses of light.
- DICC (Daresbury International Collaboration) working on new cryo-module to be tested with beam.

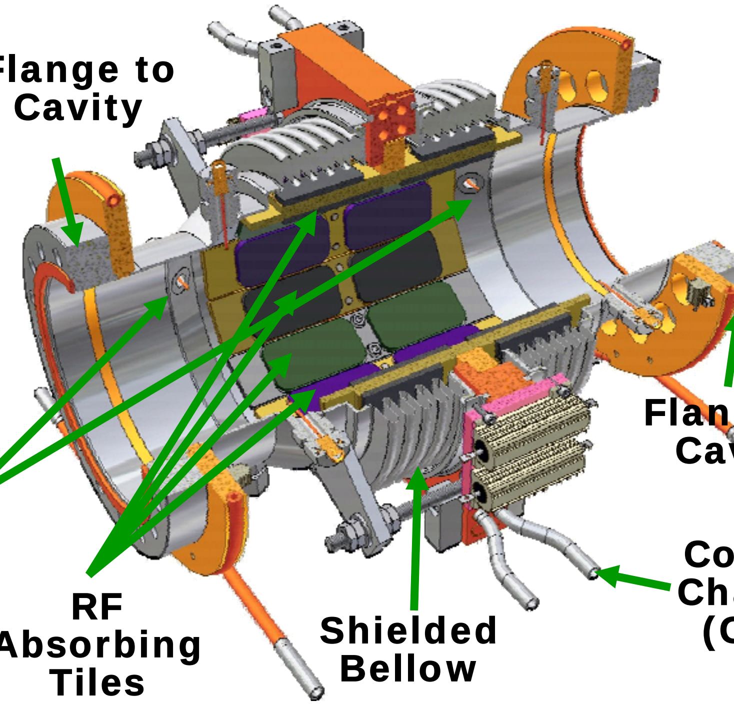


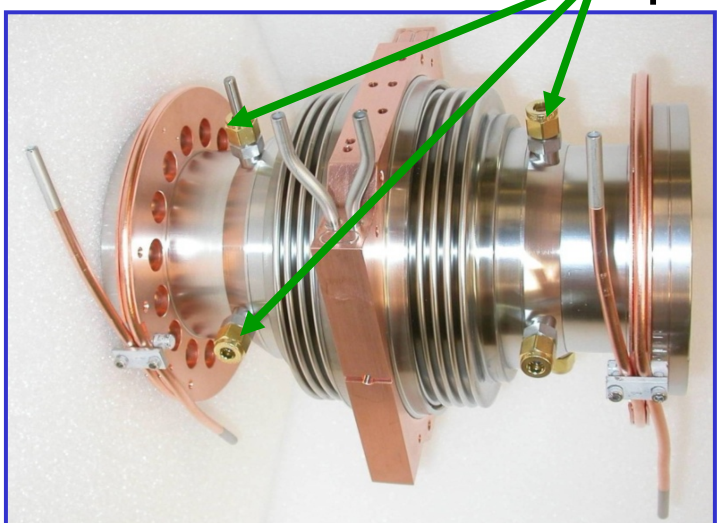


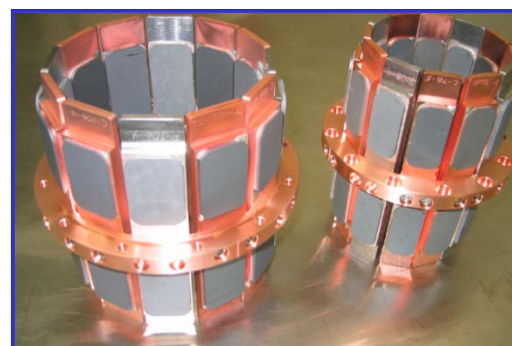
http://alice.stfc.ac.uk/accelerator

4. HOMs in Energy Recovery Linacs

Total # loads	3 @ 78mm + 3 @ 106mm
Power per load	26 W (200 W max)
HOM frequency range	1.4 – 100 GHz
Operating temperature	80 K
Coolant	He Gas
RF absorbing tiles	TT2, Co2Z, Ceralloy





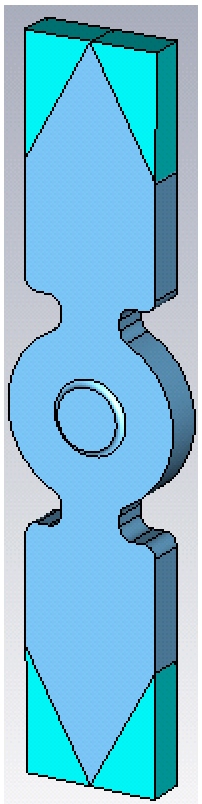


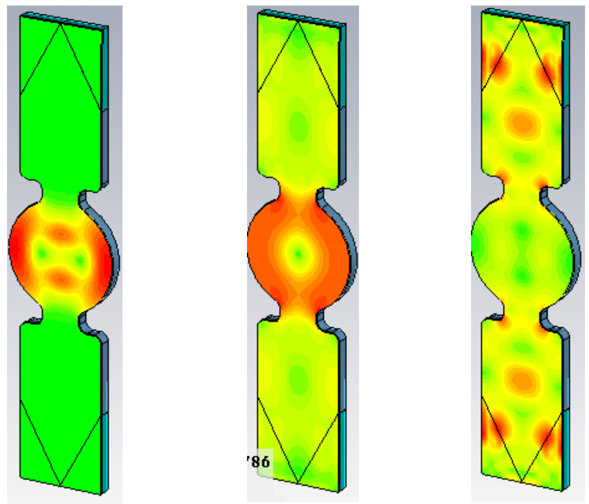
Ref: S. Belomestnykh, ERL09 Workshop, Cornell Univ.

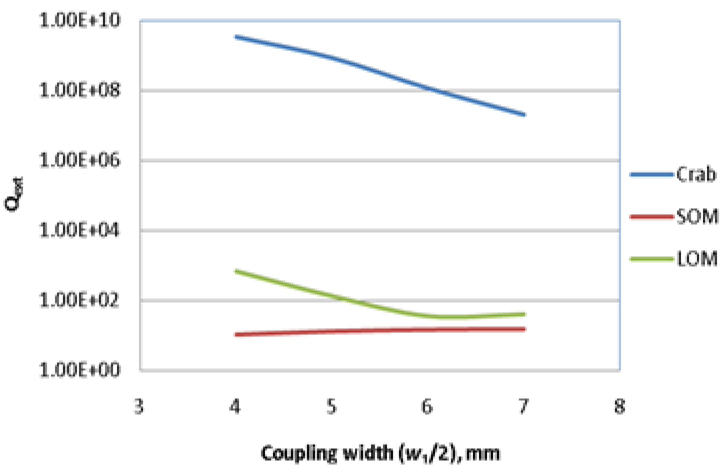
DICC HOM loads

5. HOMs in Crab Cavity

Cut-off waveguide attached to the cavity couples to the cavity modes with high current density at the equator. Thus the LOM,SOM and horizontal HOMs are removed.





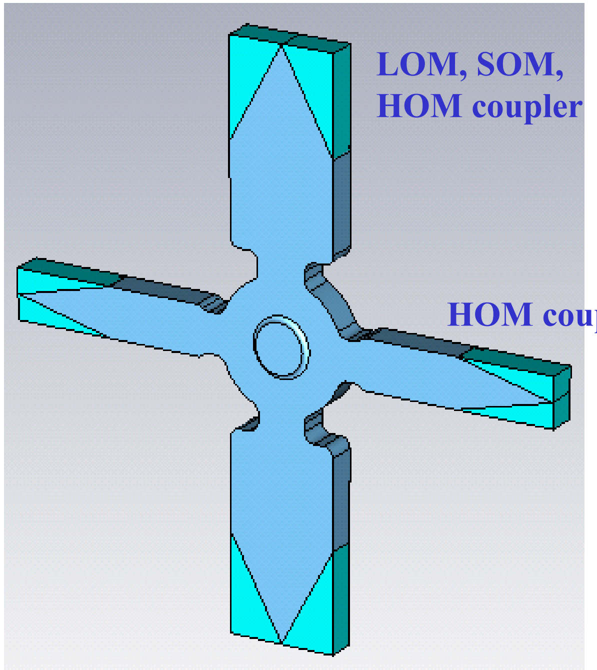


Mode	Crab	LOM	SOM
Q_{ext}	9e8	130	13

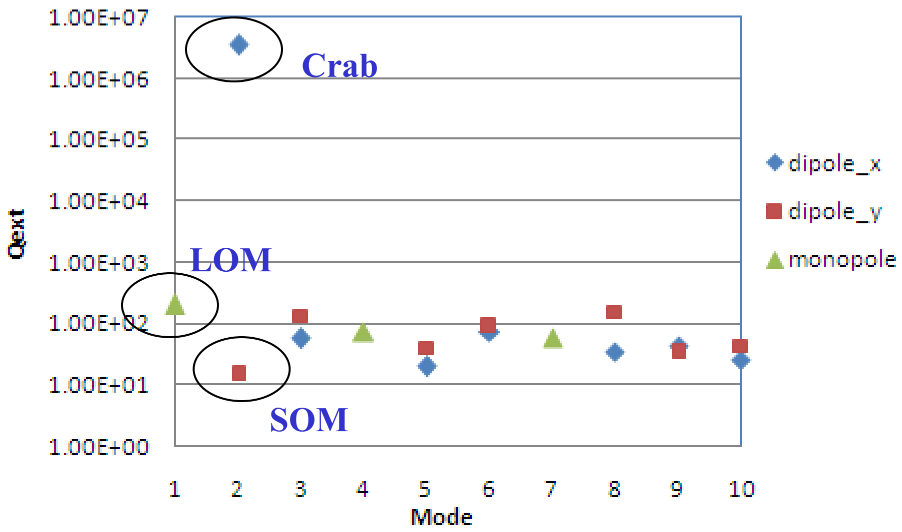
However the vertical HOMs are not picked up by the waveguide

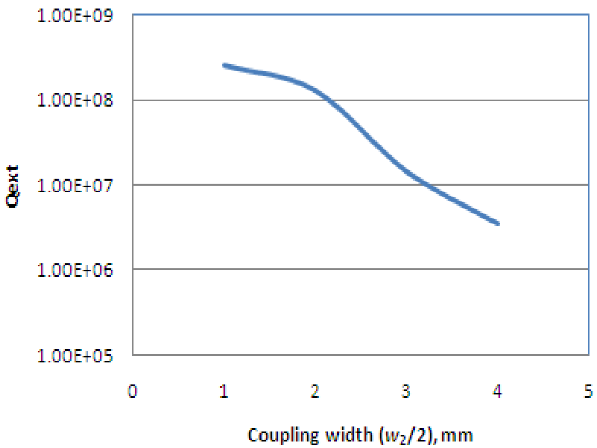
Waveguide Damping of HOMs

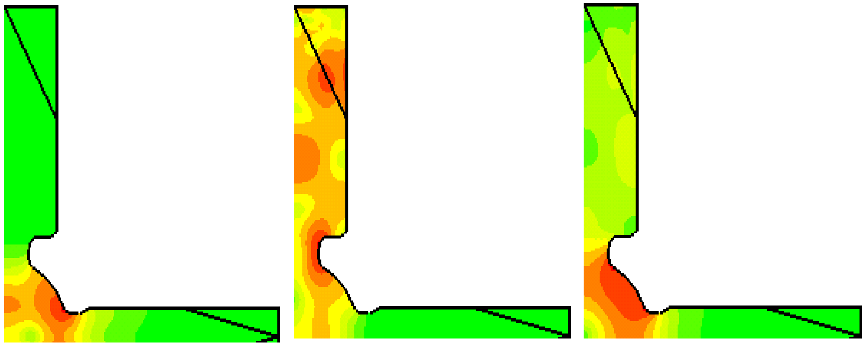
5. Vertical HOMs in Crab Cavity



A second set of waveguides which cut-off to the operating mode, damps all HOMs



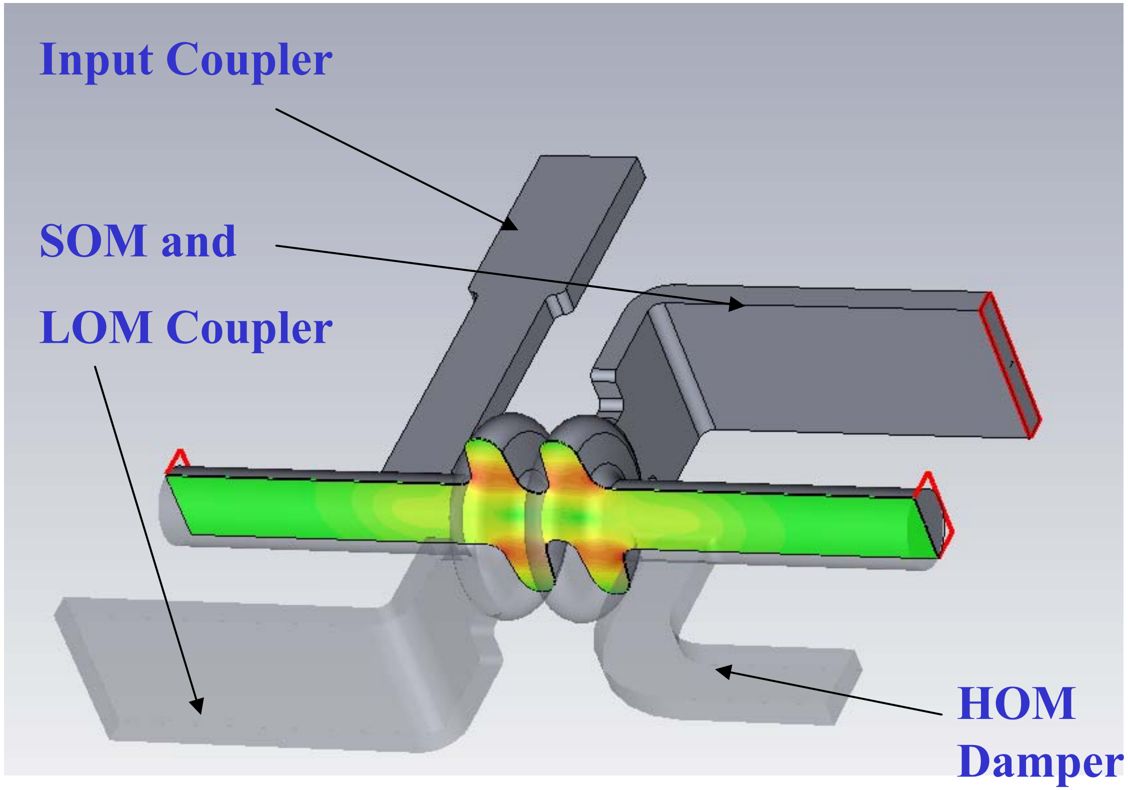


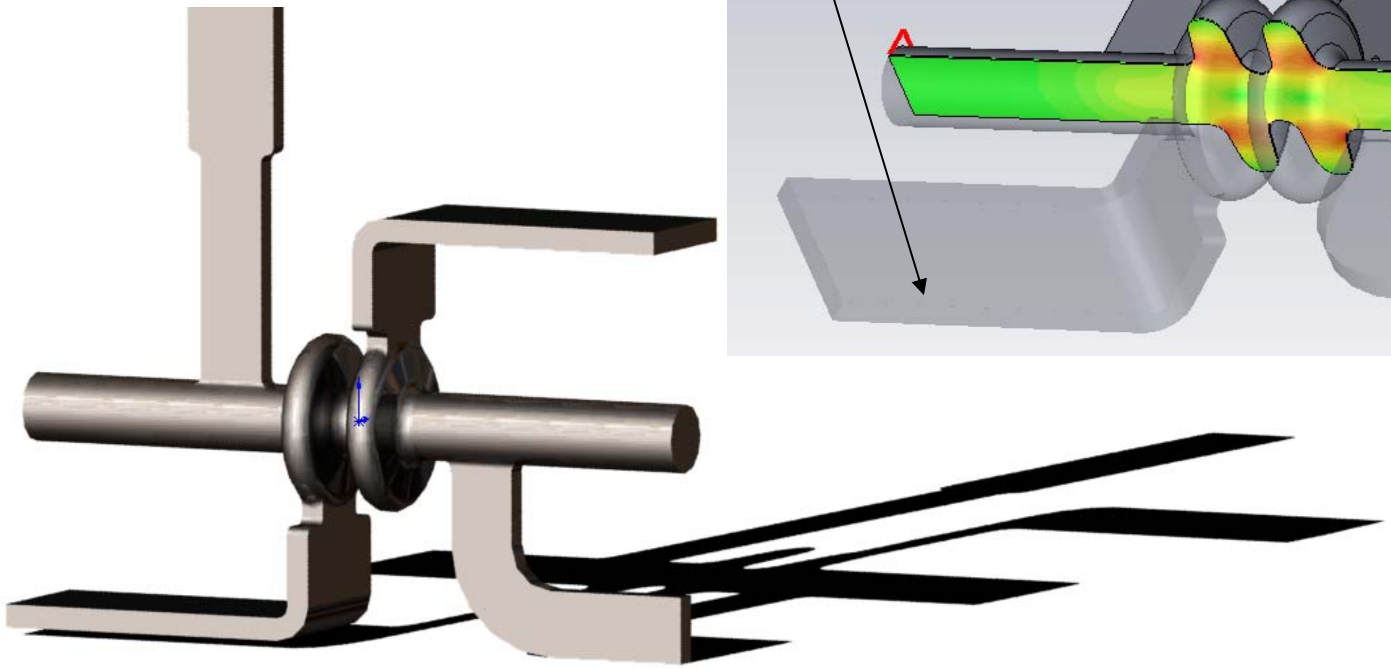


Crab SOM LOM

5. HOMs in LHC Crab Cavity

Waveguides are directly coupled to the cavities to provide significant damping. The coupling slots are placed at the field nulls of the crabbing mode to avoid high fields.





Vertical couplers only to meet the tight horizontal space requirements.

Ref: G. Burt, *Transverse deflecting cavities*, RF CAS 2010.

6. Summary

- **HOMs in both SC and NC cavities active areas of R&D**
- **HOM mitigation in RF cavities is a vibrant area –with ample opportunity to make innovative contributions**
- **NC high gradient cavities generate intense HOMs and requires careful damping to minimise emittance dilution –remember SLAC!**
- **Manifold damped (DDS) structures provides: 1. built-in BPMs and structure diagnostic, 2. vacuum pumping, in addition to 3. HOM suppression!**
- **New cavity designs (e.g. CLIC main linac, LHC & CLIC crab) illustrate the opportunity to innovate!**