6.3 Important Aspects – NLC Structure Studies as Practical Examples

For more than ten years, scientists and engineers have developed various brand new types accelerator structures and RF systems for Next Linear Collider. Although they are part of the NLC research project, but the most important aspects in design theory, computation and analysis methods, fabrication technologies, test and experimental studies are applicable to any long pulse, high gradient, strong current accelerators. It is impossible to cover all the details in a short course, but as practical examples, we try to briefly introduce you the up-to-date development in the following topics by means of visual aids.

6.3.1. Electrical Design

- Specific requirements
- Introduction to basic design procedure and method
- Idea of dipole mode detuning
- How to choose primary structure RF parameters
- Weak damping for dipole mode, damped detuned structures (DDS)
- Examples of structures

6.3.2. Structure Simulation and Computation

- Introduction to computer codes for structure design
- Precision frequency domain codes for cavity dimension
- Time domain codes for special structure components
- Long range wakefield simulation

6.3.3. Mechanical Design and Fabrication Technology

- Introduction to structure fabrication procedure
- Accelerator cavity fabrication
- Dimensional tolerances, feedforward correction application
- Cell stacking. diffusion bonding and brazing
- Mechanical QC

6.3.4. Microwave Measurement and Characterization

- Introduction to microwave measurement methods
- Microwave QC for single accelerator cavity
- Microwave QC for accelerator cavity stack
- Resonant perturbation technique
- Non-resonant perturbation technique
- Accelerator tuning set-ups

6.3.5. Some Experiments

- Next Linear Collider Test Accelerator (NLCTA)
- Principle of beam loading compensation and experiment results
- Beam experimental measurement for wakefields

6.3.6. High Gradient Operation

- Field emission at high gradient
- RF breakdown
- RF processing of structures
- Problems in high gradient operation
- Structure damage, observation and analysis
- Program to improve high gradient performance

Specific Requirements of Accelerator Structures for Linear Colliders

- **High Accelerating Gradient** to Optimize Length and Cost.
- **Control of Short and Long-Range Wakefields** to Ensure the Preservation of Low Emittance for Multi-Bunch Beams.

Design Procedure and Method

- Choose Basic Parameters: length, filling time, attenuation factor based on the RF source and system ($\tau \sim 0.5$, Tf ~ 100 ns for optimized efficiency)
- Choose Iris Size and Dipole Detuning Range based on beam emittance and wakefield suppression requirements ($a \sim 0.18\lambda$, 10% f1 detuning)
- Optimize Cavity Shape for best shunt impedance, r/Q, low E_s
- Calculate Wakefields from equivalent circuit and spectral function analysis using optimized HOM coupling slots and manifold size
- Create Cell Dimension Table using high accuracy 3D modeling for typical cells, then to extrapolate.
- Design and Simulate Special Potions of the Structure like input coupler, output coupler, HOM couplers
- Fabricate, Mechanical QC and Microwave QC typical cells and special coupler parts for final corrections of essential geometries
- Perform Mechanical Design to ensure electrical properties and manufacturability

Filling Time vs Attenuation Factor

•In constant gradient structure

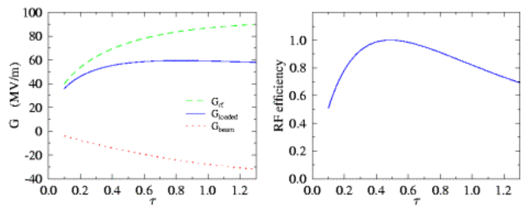
$$V_{rf} = \sqrt{P_{in} r L (1 - e^{-2\tau})}$$

$$V_b = -\frac{I_0 r L}{2}\left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}}\right) \quad \text{and} \quad \tau = \frac{\omega L}{2 Q v_g}$$

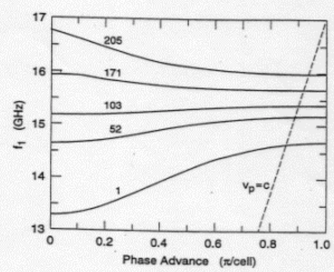
•Efficiency for given center-of-mass energy at IP

$$\propto G_L^2 / (P_{in}(t_F + t_b))$$

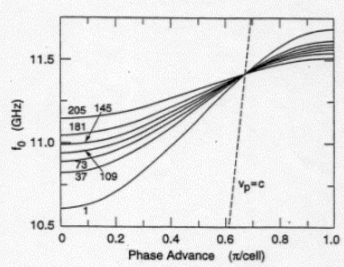
•Optimal τ around 0.5 $\rightarrow t_f$ of ~100-ns



Idea of Dipole Mode Detuning



Dispersion curves of dipole modes, for the simplified detuned structure.



Dispersion curves of TM_{01} modes, for the simplified detuned structure.

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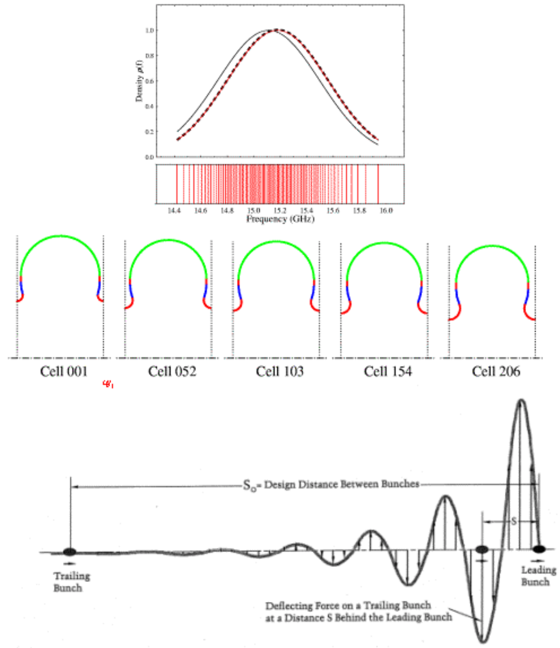
How Detuning Works



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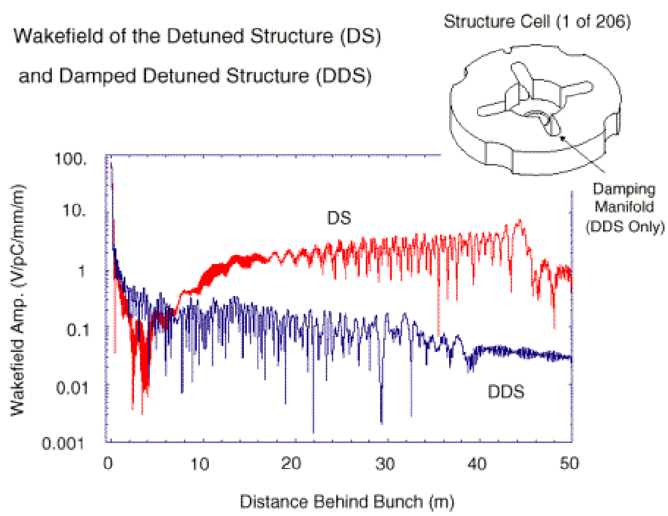
Wakefield of Deflecting Modes for Different Structures



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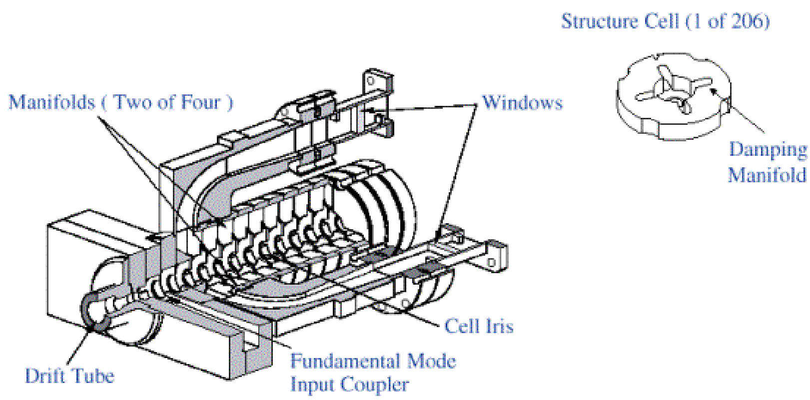
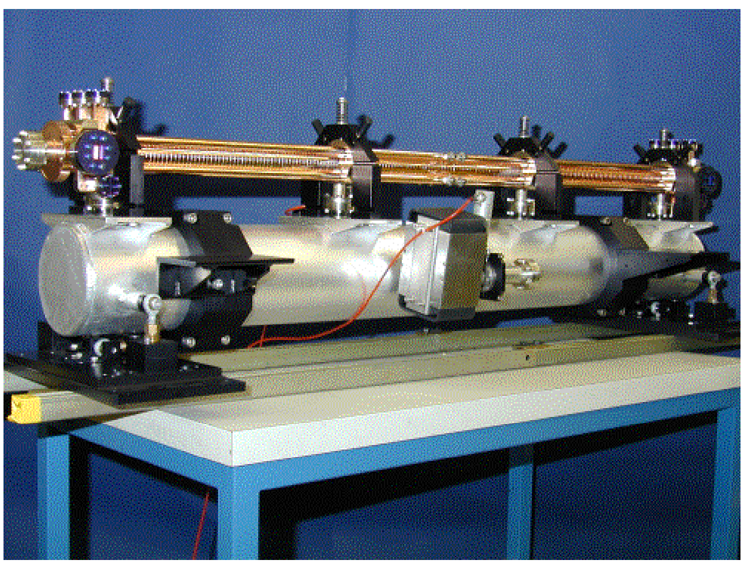
Cutaway View of DDS Structure

Interior Views of the Damped and Detuned Structure (DDS)



DDS3 Structure on Strongback



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Structure Design Codes

• 2D cell profile	Omega2
• Dimensions of Detuned Structure (DS)	
• Damping manifold and coupling slots	MAFIA, circuit
• Final 3D dimensions of sample cells	Omega3P
• 3D machine table dimensions	
• Couplers and special cells	MAFIA, Tau3P

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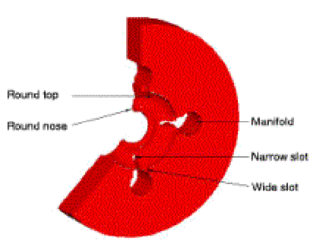
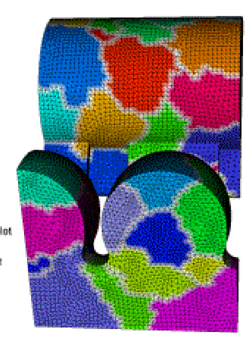
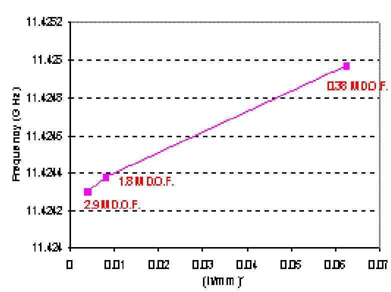
Design 3D Cell Dimensions Using *Omega3P*

- Calculate 7 cells along the structure
- Fit using Spline function to obtain parameters of other cells
- Correct skin depth and temperature → final machine table
- Omega3P sub-MHz (sub-micron in "b") accuracy confirmed by coldtest



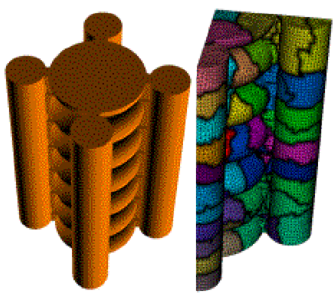




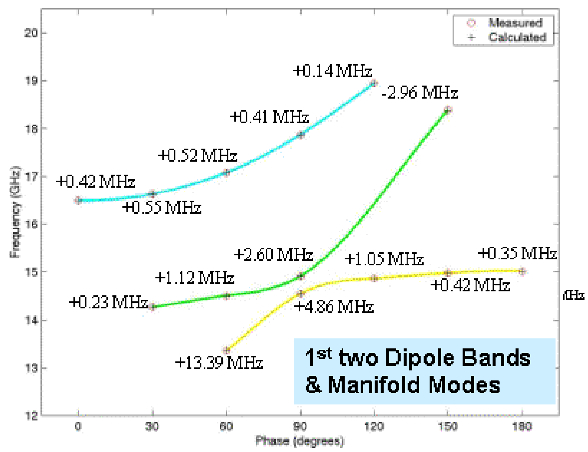
T3E: #Elem=60K, #DOF=380K, #proc=16, T=19 min
- Quadratic Formulation With Curved Surface
- Reach frequency accuracy of 0.01%

RDDS 6-Cell Stack – Frequency Domain

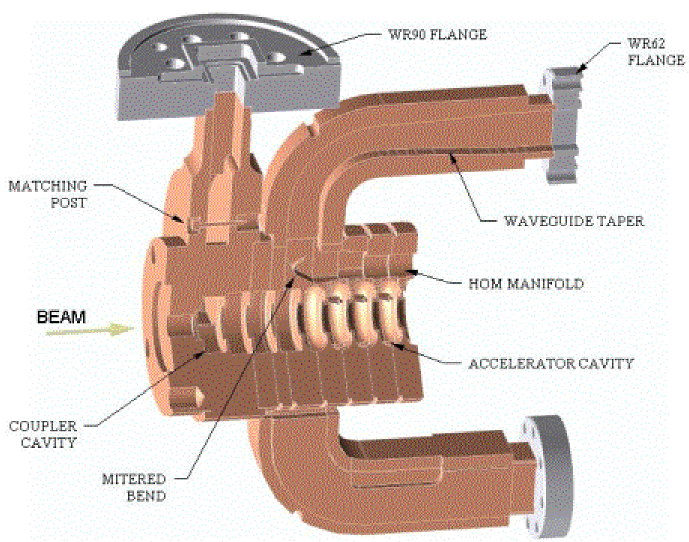
Higher Order Modes in RDDS 6-Cell Stack – Good Benchmark of Omega3P against Measured Data



SP2: Elem=275K, DOF=1.7M, #proc=48, T=1 hr



Cutaway View of RDDS1 Input End



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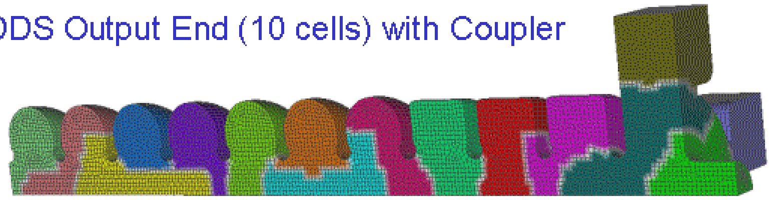
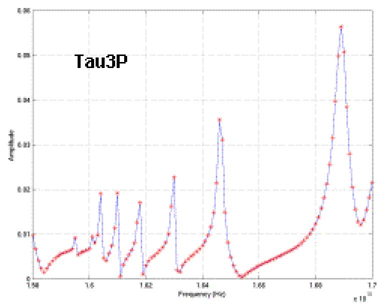
Tau3P Benchmark (Field Excitation)

RDDS Output End (10 cells) with Coupler



Dipole Mode Spectrum



Measurement	Tau3P
16.868 (350)	16.89 (400)
16.440	16.46
16.280	16.30
16.176	16.18
16.098	16.10
16.034	16.04

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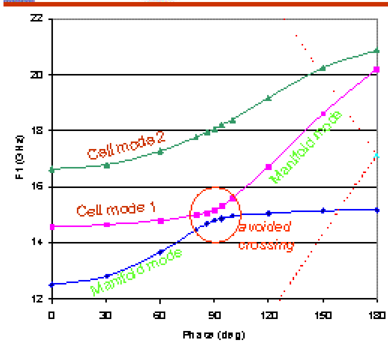
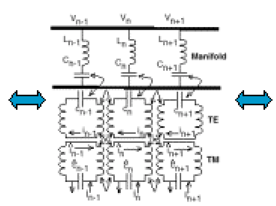
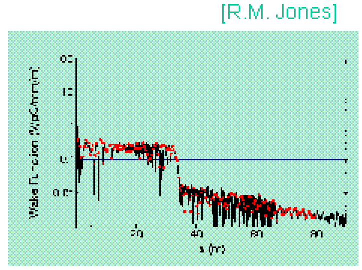
Long-Range Wakefields





[R.M. Jones]



- Treat each cell as periodic
- Calculate 5 sample cells (MAFIA)
  - ✓Dispersion curves
  - ✓synchronous kick factor
  - ✓avoided crossing (coupling)

- Fit dispersion curves of sample cells to obtain cell parameters
- Interpolate to obtain parameters of all cells

- Solve coupled circuit system
- Integrate spectrum for wake
  - ✓Optimize cell-manifold coupling
  - ✓Optimize "UN"-coupled spectrum

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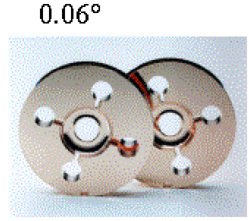
Fabrication Procedure

- Rough Machining or Single Diamond Turning
- Ozonized Water Rinsing or Chemical Cleaning
- Cell Stacking
- Pre-Bonding at 150^0 C and Final Diffusion Bonding at 850^0 C for Single Diamond Turning Cavities
- Diffusion Bonding at 1050^0 C for Regular Machining Cavities
- Chemical Cleaning for Input/Output/HOM Parts
- Final Brazing for Couplers and Other Attachments
- Leak Check and N2 Purge
- Microwave Characterization
- Wet H2 firing and Dry H2 firing at 950^0 C
- Vacuum Baking at 650^0 C for 2 weeks
- Alignment Measurement and Straightening
- Wakefield Measurement
- In-situ Vacuum Baking at 220^0 C for one week
- High Power Processing

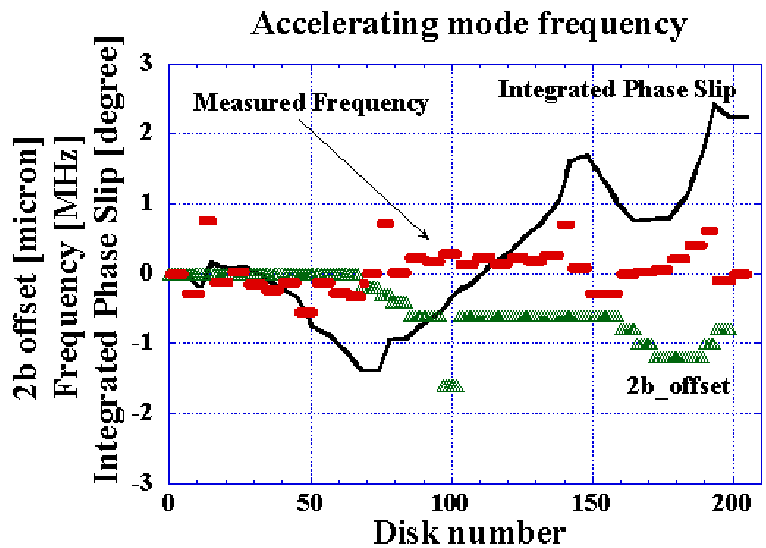
SLAC

Summary of RDDS1 Dimensional Properties

Item	Design	Typical	Worst
Flatness	0.5 µm	<0.5	0.6
Thickness	±1 µm	< ±1	1.5
Parallelism	17 µrad	<10 µrad	25 µrad
OD	±1 µm	< ±1	1.5
2D Contour	±1 µm	< ±1	
2a	±2 µm	< ±0.7	0.7
2b	±2 µm	< ±1	1.3
Gap	±1 µm	< ±0.5	0.5
Concentricity	±0.5 µm	< ±0.5	2.0
Slit Width	±15 µm	< ±5	10
Slit Depth	±30 µm	< ±10	15
Rotational Angle	±0.05°	<0.05°	0.06°
Bookshelf	50 µrad	<100 µrad	
Misalignment	±3 µm	±1	



Stack Microwave QC and Feedforward Correction



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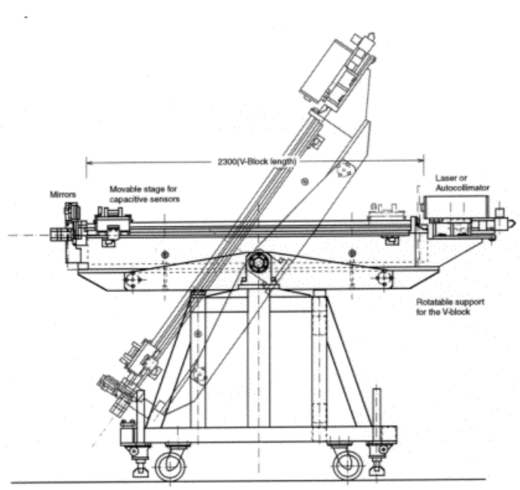
Cell Stacking Frame



Second Assembly Brazing for RDDS1

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Mechanical Measurements

Measurement Method	Purpose
1. CMM Machine	Profile Confirmation Design Stage Fabrication Stage Straightness Bookshelving
2. Zygo Machine	Flatness
3. Capacitive Sensors System	Stacking Alignment & Straightness
4. Autocollimator	Stacking Angles & Bookshelving
5. Optical Microscope	Surface Studies
6. SEM	Surface Studies
7. Boroscope	Surface Studies
8. Advant	Non-contact Profile Measurement

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Microwave Measurements

Measurement Method	Purpose
1. Resonant measurement of Single cavity	Quick QC
2. Resonant measurement of Stack of cavities	Modes studies/Feedforward
3. Resonant measurement using a pair of antennas	Tuning assembled structures
4. Nodal shift technique using metal plunger	Tuning assembled structures
5. Non-resonant perturbation method	Tuning assembled structures Final QC

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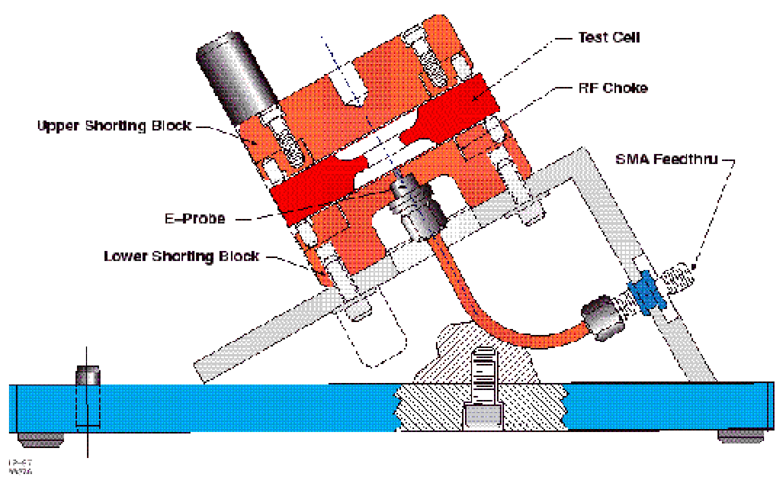
Microwave QC for Single Disk

Cell Microwave QC Test Set



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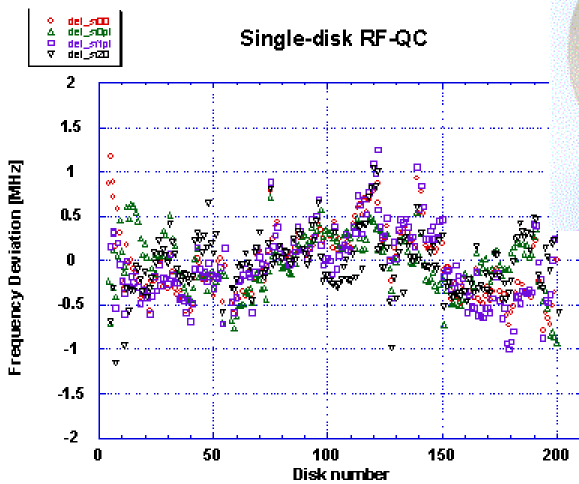
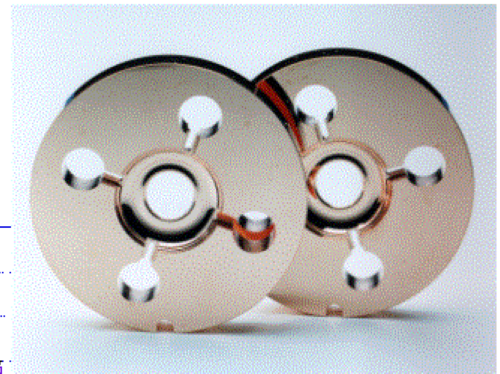
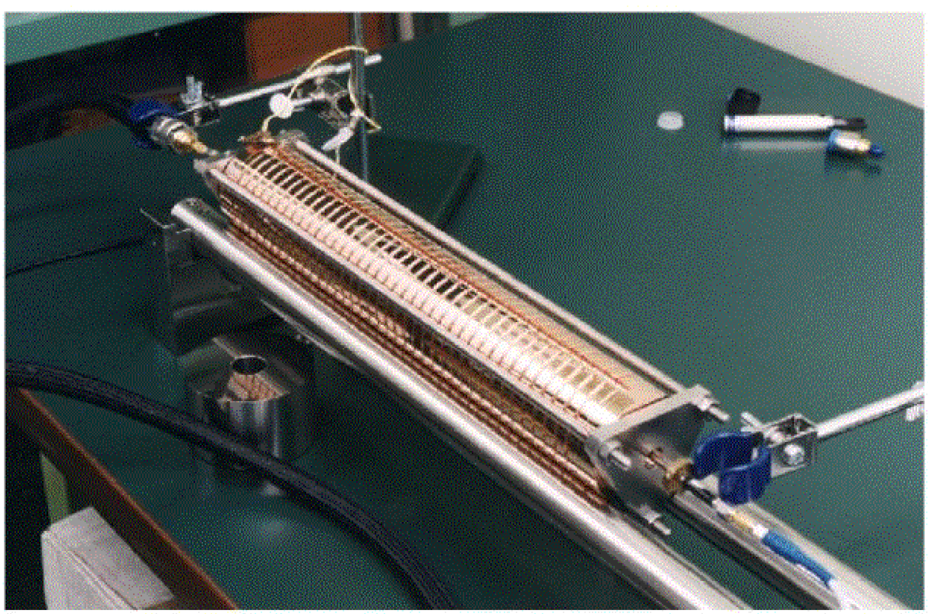
Single Disk Microwave QC Results

Cavity profile ± 1μm
Outer diameter ± 1μm





Stack Microwave QC Setup



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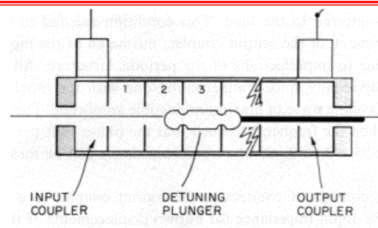
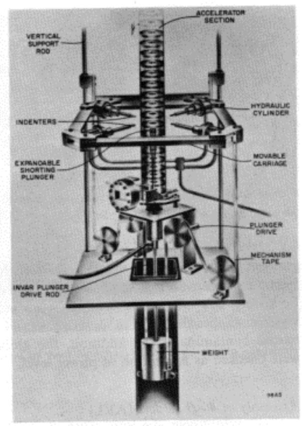
TW Structure Tuning

Nodal Shift Technique



Tuning Mechanism For SLAC 10-foot Section



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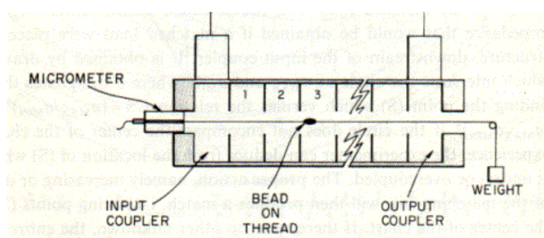
Non-Resonant Perturbation



Reflected wave amplitude is

$$E_r(z) = K\frac{E^2(x,y,z)}{P(z)}E_i(z)$$

Where K is a constant which depends on the bead,
E(x,y,z) is the forward power flowing across the structure at z,
Ei is the incident wave amplitude.
The reflection coefficient is defined as: $\rho(z) = \dfrac{E_r(z)}{E_i(z)}$

For constant gradient structure:

$$\rho(0) = \frac{E_r(0)}{E_i(0)} = K\frac{E^2(x,y,z)}{P(0)}$$

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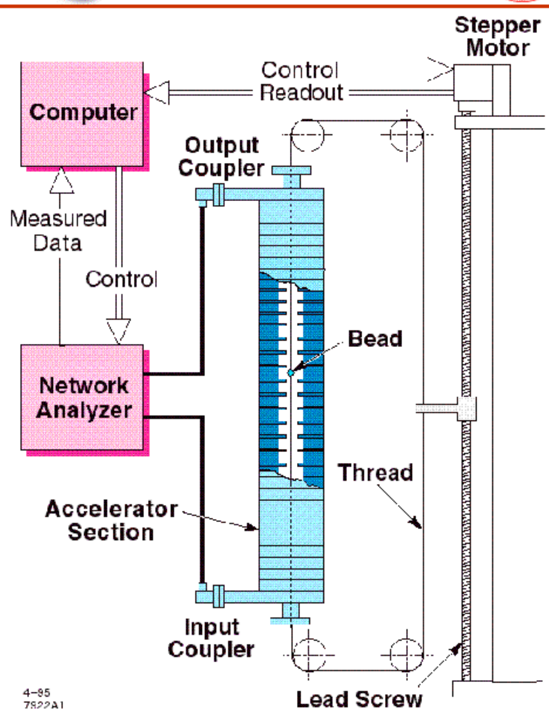
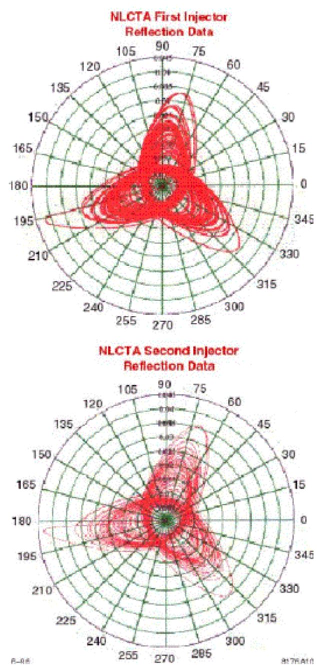
Bead Pulling Setup



Bead Pulling Results-I



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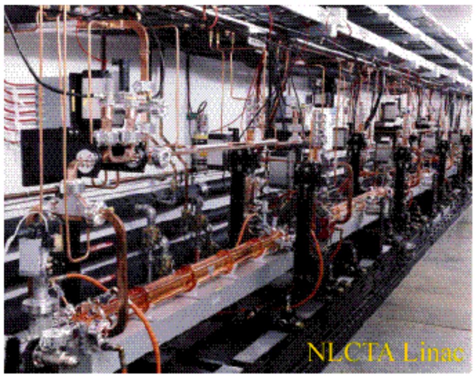
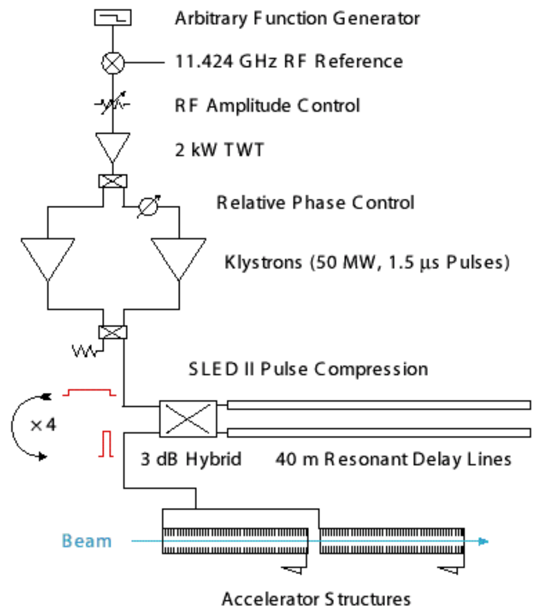
Next Linear Collider Test Accelerator (NLCTA)

- Construction Started in 1993 Using First Generation RF Component Designs.
- Goals: RF System Integration Test of a Section of NLC Linac and the Efficient, Stable and Uniform Acceleration of a NLC-like Bunch Train.
- In 1997, Demonstrated 15% Beam Loading Compensation of a 120 ns Bunch Train to < 0.3%.

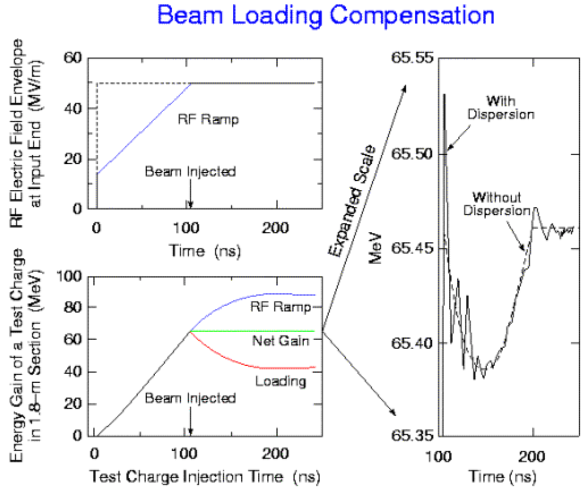


NLCTA Linac RF Unit (One of Two)



Principle of Beam Loading Compensation

Beam Loading Compensation

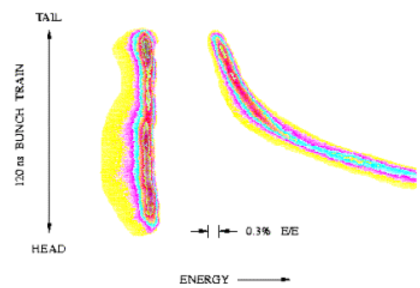


Experiment Results of Beam Loading Compensation

BEAM LOADING COMPENSATION

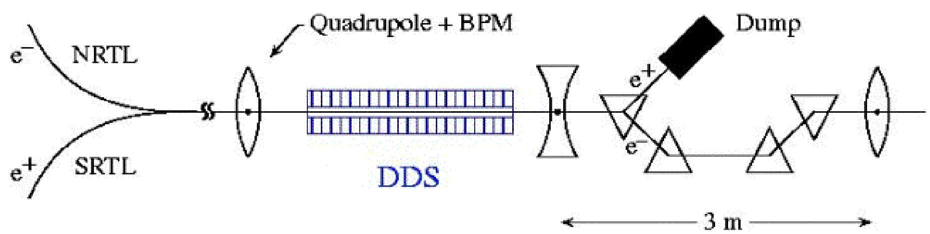
Method: Ramp RF Amplitude During Fill

Verification: Observe E Variation Along Bunch Train

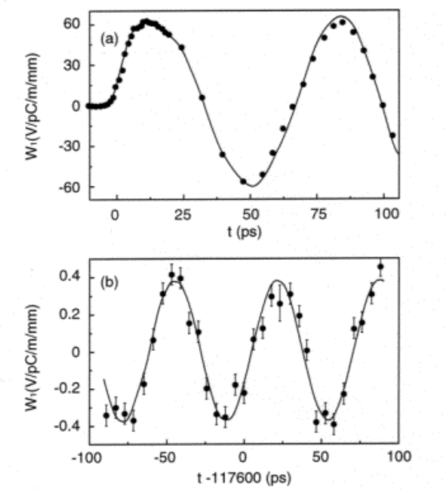


RF Station	Unloaded Gradient (MeV/m)	% Loading
0	47	14
1	44	17
2	37	17

Schematic ASSET Facility
(Accelerator Structure SETup)



Wakefield Measurement



Dipole wakefield measured near the driving bunch crossing (top plot) and 118ns behind driving bunch (bottom plot).

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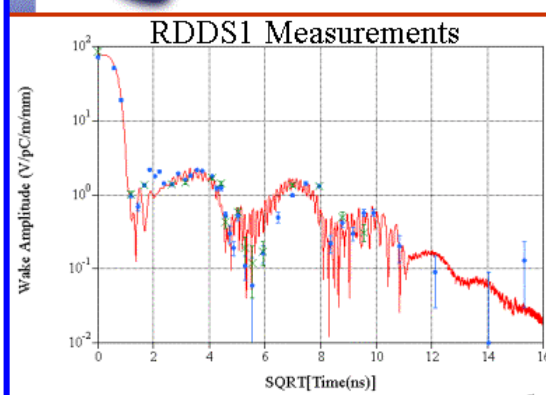
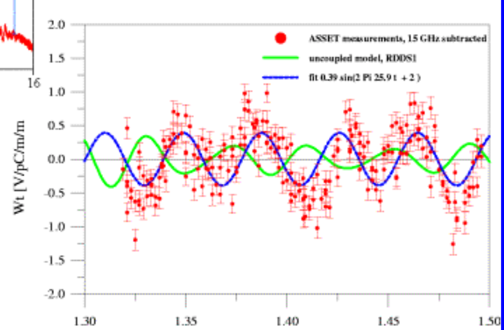
Wakefield Measurements

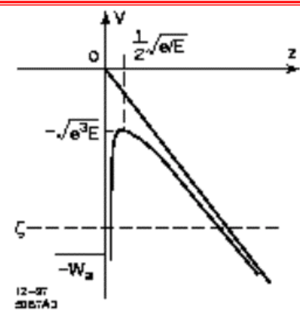


- Three DDS-style structures have been built and tested
- Wakefield model agrees well with measurements

- Lowest band is around 15 GHz
- Next band (25 GHz) is visible after 1.4 ns



Field Electron Emission



Potential energy diagram showing the modified electric field potential barrier
DC Field electron emission from ideal metal surface:

$$V(x) = \begin{cases} -W_a & x<0 \\ -eEx - \dfrac{e^2}{4x} & x>0 \end{cases}$$

Conduction electron obey Fermi-Dirac statistics -- Flux $N(w_x)dw_x$
Tunneling probability can be calculated --- Time-independent Schrodinger equation solution $D(w_x)$

Integrate
$$j_F = \int_{-\infty}^{\zeta} D(w_x)N(w_x)dw_x$$

$$j_F = \frac{1.54\times10^{-6}\times10^{4.52\phi^{-0.5}}E^2}{\phi}\exp\left(-\frac{6.53\times10^9\phi^{1.5}}{E}\right)(A/m^2)$$

Where the electric field E(v/m) and work function φ(eV)

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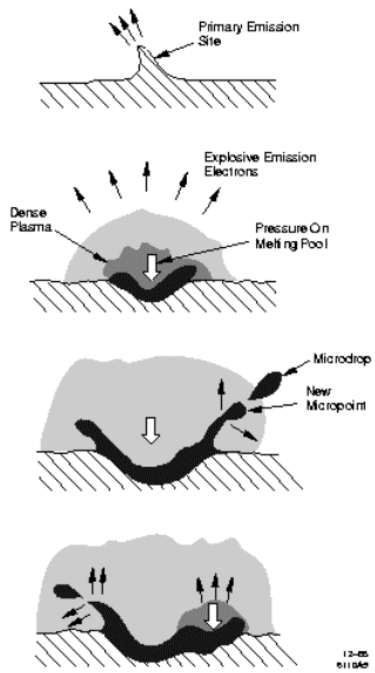
Explosive Electron Emission



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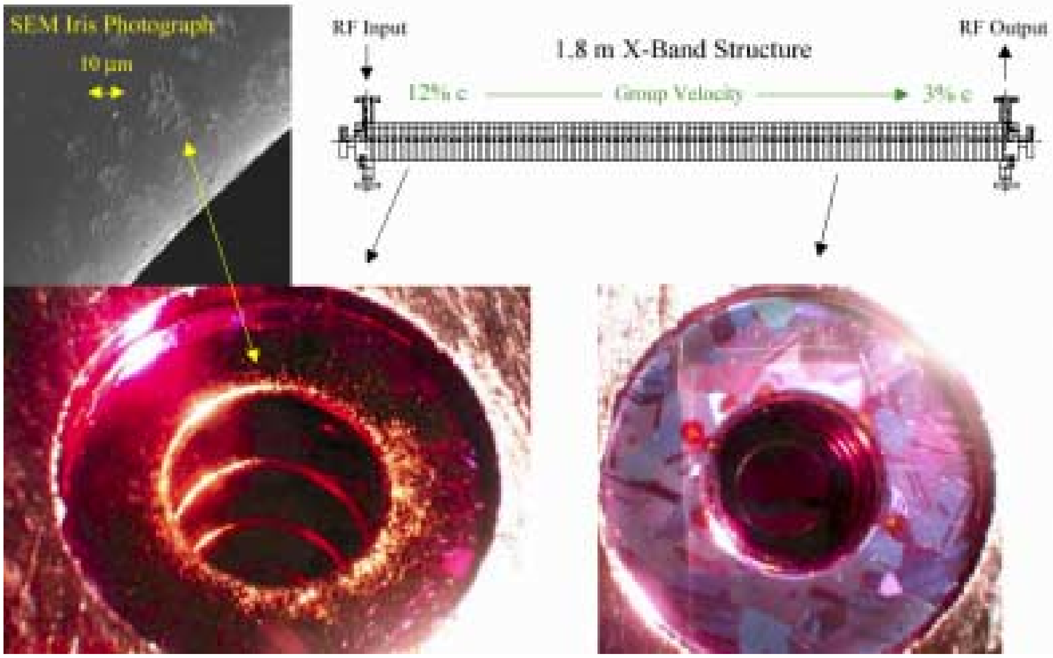
Pitting on Cell Irises of a 1.8 m Structure After Operation at Gradients up to 50 MV/m



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Program to Improve High Gradient Performance

• Compare performance versus different:
– Initial structure group velocity (5 % and 3% c) and length (20, 53 and 105 cm)
– Cell machining (single and poly diamond) and cleaning (etch time) methods
– Structure type: standing- wave -vs- traveling- wave.
_ Thus far have processed 12 structures (> 5000 hours operation at 60 Hz).
• Systematic study of rf breakdown
– Measure RF, light, sound, X- rays, currents and gas associated with rf breakdown in structures, waveguides and single cavities.
– Simulate breakdown effect on RF transport with 'MAGIC' particle- in- cell code.
– Measure surface roughness/ cleanliness/ damage with SEM, EDX, XPS and AES.
• Improve structure handling and cleaning methods
– Adopted better degassing procedure that includes:
• Wet and dry H_2 firing
• 650 °C vacuum bake for 16 days
• 225 °C in- situ bake for 7 days.

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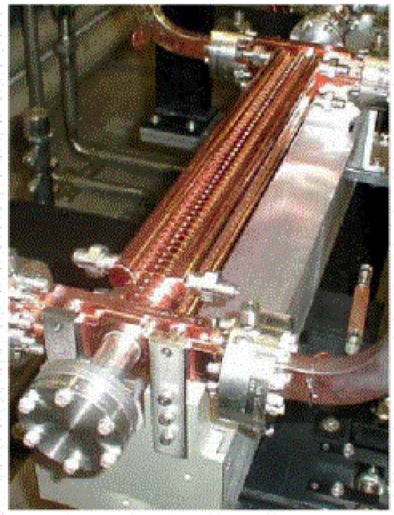
Low Group Velocity Traveling Wave Structures

T53VG3: 53 cm long, 60 cells



- Best performance thus far with 3% c initial group velocity structures.
- One was processed to 86 MV/ m, after which breakdown rate at 70 MV/ m was about 1 in 200,000 pulses, dominated by input/ output coupler events. Rate at 65 MV/ m was about 10 times smaller, which would be acceptable for the NLC.
- Damage level small during processing (1/ 2° phase shift) – tolerable for NLC even if increased at same rate after processing, which has not been observed.
- Tests of 3% c and 5% c initial group velocity structures with improved couplers, NLC- acceptable iris radii and wakefield detuning are scheduled this year – versions with wakefield damping will be ready in early 2003.

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Standing Wave Structures

(15 Cells, 20 cm Long, 124 ns Field Rise Time)

- In NLC, standing- wave structures would operate at the loaded gradient of 55 MV/ m.
- In recent tests, breakdown rates of < 1 per 8 million pulses were measured at this gradient and the structures showed no discernable damage ($\Delta f/f < 10^{-5}$) after processing, making this design a candidate for the NLC.
- Next round of structures will have lower surface fields and wakefield detuning – incorporating wakefield damping will take 1- 2 years.