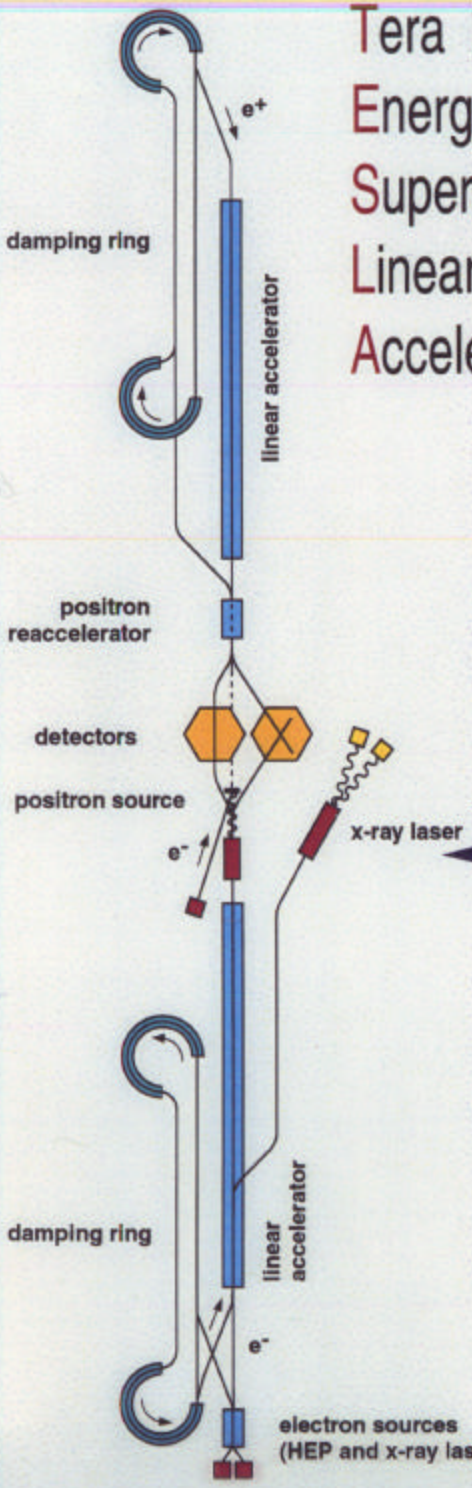
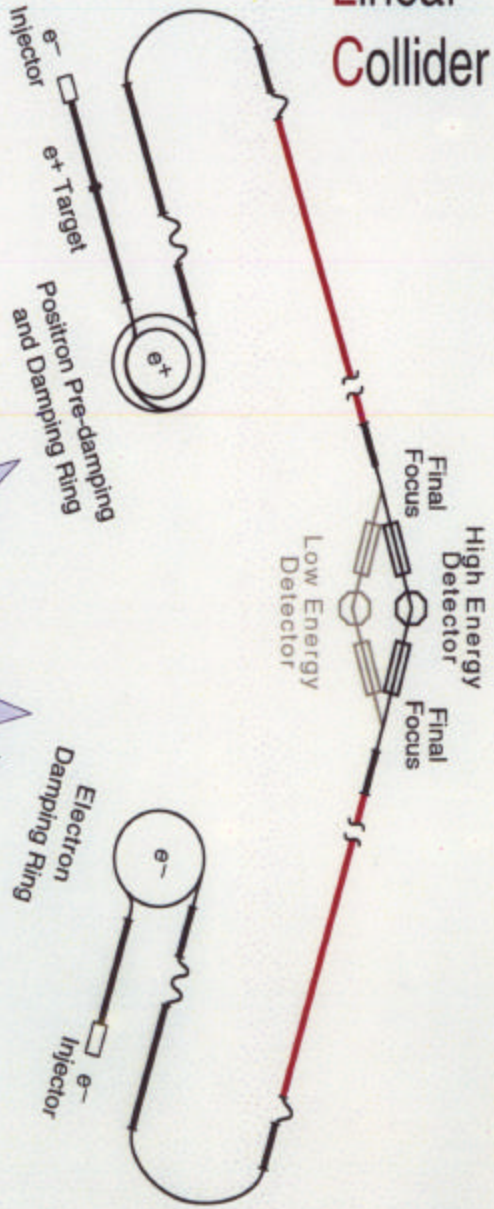
Tera Electron Volt Energy Superconducting Linear Accelerator



POWER To The BEAM

Next Linear Collider



Chris Adolphsen

Luminosity ($\mathcal{L}$) and Beam Power (P_{beam})

For NLC & TESLA, $\mathcal{L}$ Scales Approximately* as

$$\mathcal{L} \sim P_{beam} / (\varepsilon_y)^{1/2}$$

where

ε_y = Normalized Vertical Emittance at IP

P_{beam} = Linac Wall Plug Power (P_{AC}) — Limited to a Few 100 MW

× AC -to- Beam Efficiency — Function of RF Technology

= N_e: Number of e^+/e^- per Bunch

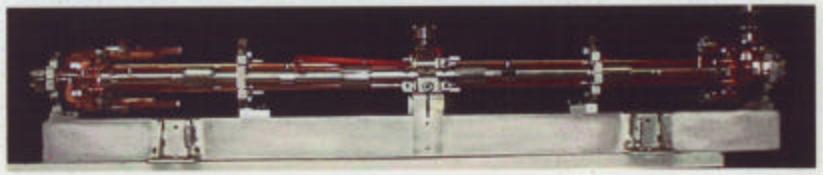
× N_b: Number of Bunches Per Pulse

× f_{rep}: Pulse Repetition Rate

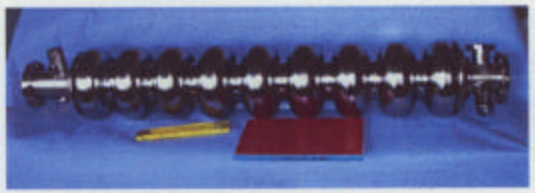
× E_b: Final Beam Energy

*Assume fixed δ_B, $\beta_y = \sigma_z$ and $\sigma_x >> \sigma_y$ at IP

RF Technology



- NLC: Normal Conducting Traveling Wave Structures
  - ➢ Choice of frequency (f) and gradient.
    - ▸ At a fixed beam current, the same RF-to-beam efficiency can be achieved at higher f with lower RF energy per pulse ($\rightarrow$ less RF components but higher f_{rep}) and higher gradient ($\rightarrow$ shorter linac).
    - ▸ However, have larger transverse wakefields (f^3) which yield tighter alignment tolerances.
    - ✓ At 11.4 GHz can obtain major cost benefits with manageable tolerances. Cost optimum at an unloaded gradient of about 70 MV/m, which is being targeted in the R&D program.



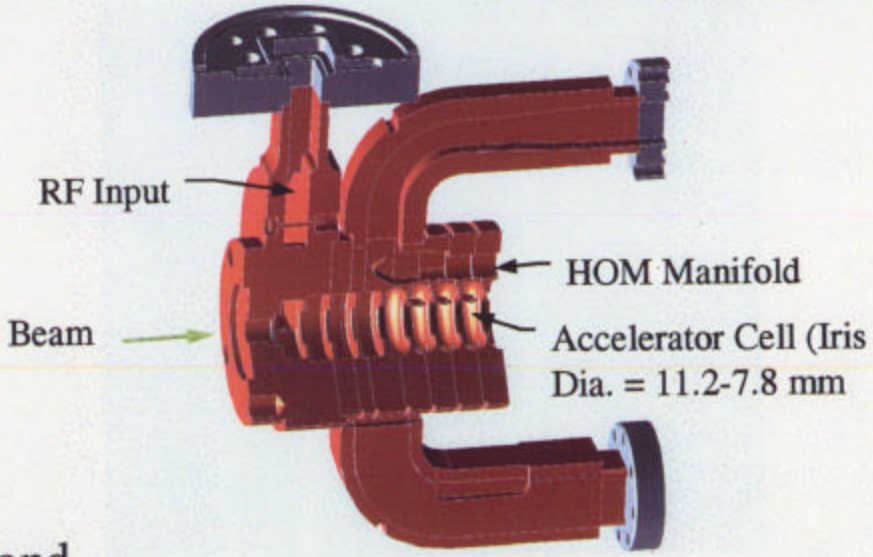
- TESLA: Super Conducting Standing Wave Cavities
  - ➢ Choice of frequency (f) and gradient.
    - ▸ RF Surface heating has a $1/f$ (surface area) times $A+B f^2$ (surface resistance) frequency dependence leading to a broad minimum in the 300 MHz to 3 GHz range.
    - ✓ 1.3 GHz chosen based on available power sources and a tradeoff on cavity size and pulse energy (high f) -vs- wakefields and thermal instability limit (low f). Design gradient of 23 MV/m based on achieved performance: cost optimum at a higher value.

Beam/RF Parameters

Quantity	Symbol	NLC	TESLA	Determined by
Bunch Spacing (T_{rf})	T_{bb}	16	438	Long-Range Transverse Wakefield Detuning: Scales as Ratio of RF Period (T_{rf}) to Dipole Mode Freq. Spread
Bunch Train Length (T_{fill})	T_b	2.6	2.3	Tradeoff of Efficiency: T_b > Structure Fill Time (T_{fill}) and Cost: Energy per Pulse and Damping Ring Size
Charge per Bunch (10^{10})	N_e	0.75	2	Tradeoff of Efficiency (N_e / $a^{0.5}$) and Short-Range Transverse Wake Kicks ($N_e \sigma_z$ / $a^{3.5}$) Short-Range Loading (N_e / σ_z / a^2)
Structure Iris Radius (λ_{rf})	a	0.18	0.15	
Bunch Length (μm)	σ_z	110	300	
Pulse Rate	f_{rep}	120	5	AC Distribution, Cooling and Operating Costs

NLC Rounded Damped-Detuned Structure (RDDS)

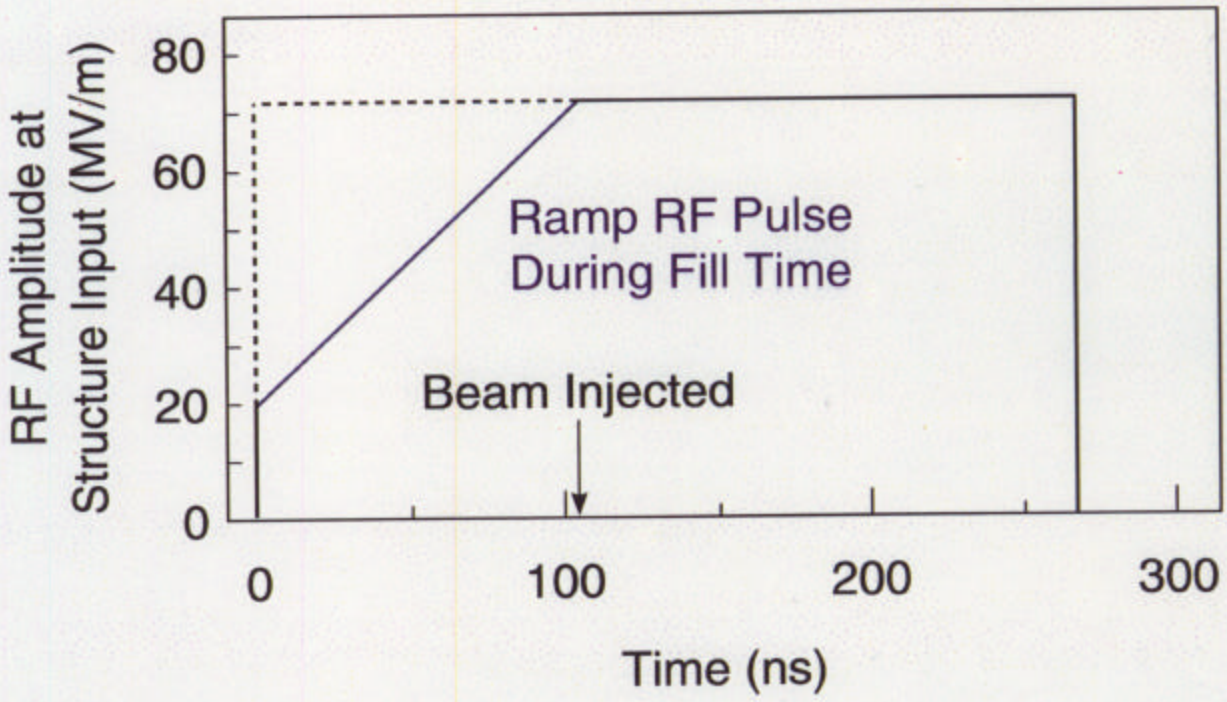
RDDS – Cutaway View
Showing 8 of 206 Cells



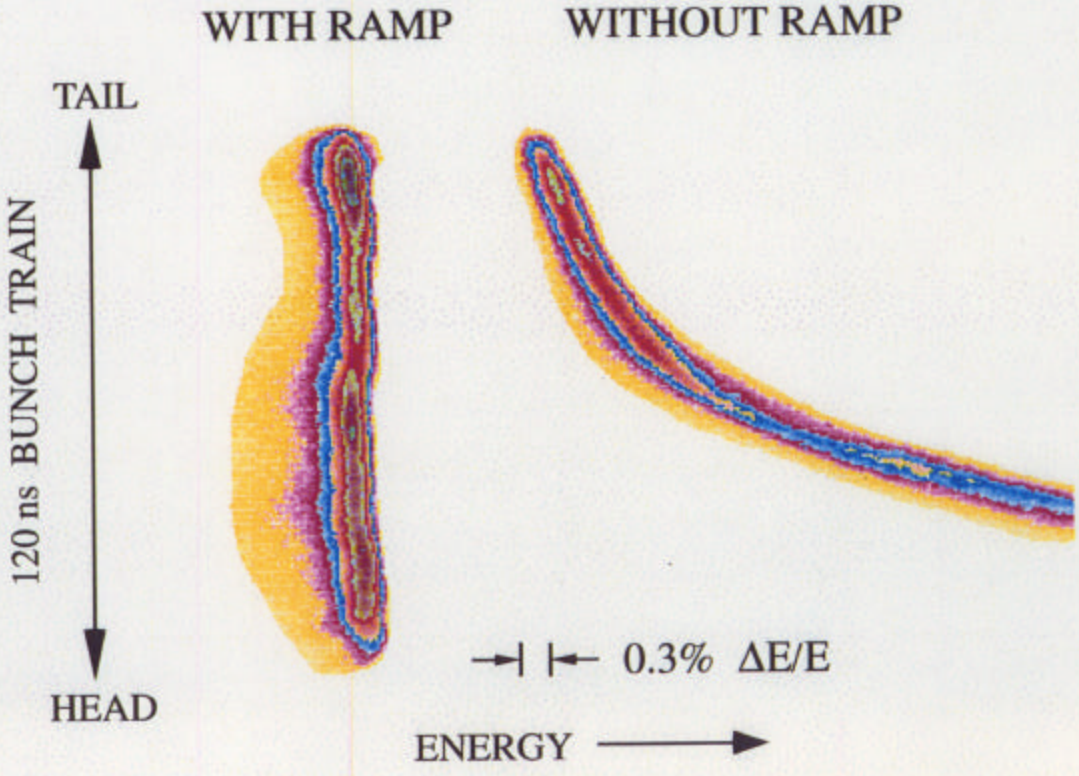
- Made with Class 1 OFE Copper
- Cells are Precision Machined (1 μm) and Diffusion Bonded to Form Structure.
- 1.8 m Length Chosen so Fill Time is ≈ Attenuation Time (Q/ω) ≈ 100 ns.
- Operated at 45 °C with Water Cooling. RF Losses are about 3 kW/m.
- RF Ramped During Fill to Compensate Beam Loading (22%). In Steady State, 52% of the 170 MW Input Power Goes into the Beam.

1 of 206 Cells

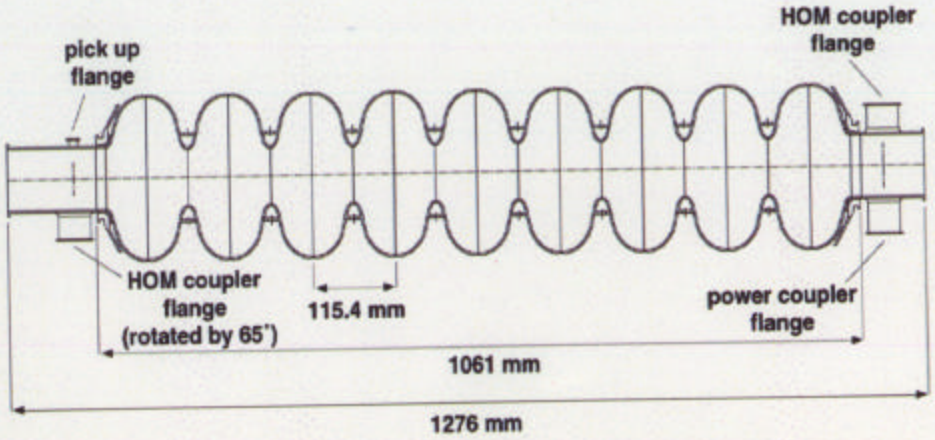
Beam Loading Compensation in NLC



NLC Test Accelerator Beam Loading Measurements

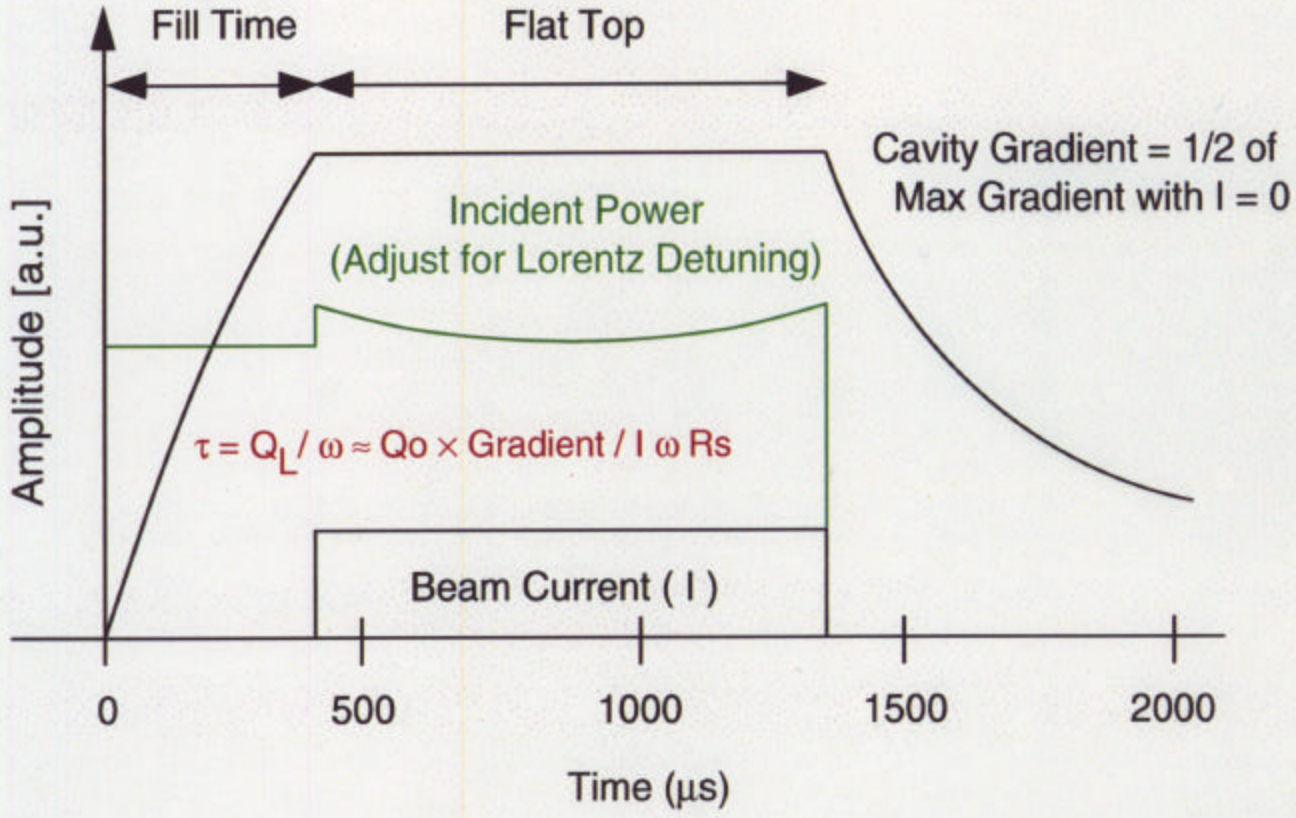


TESLA Cavities

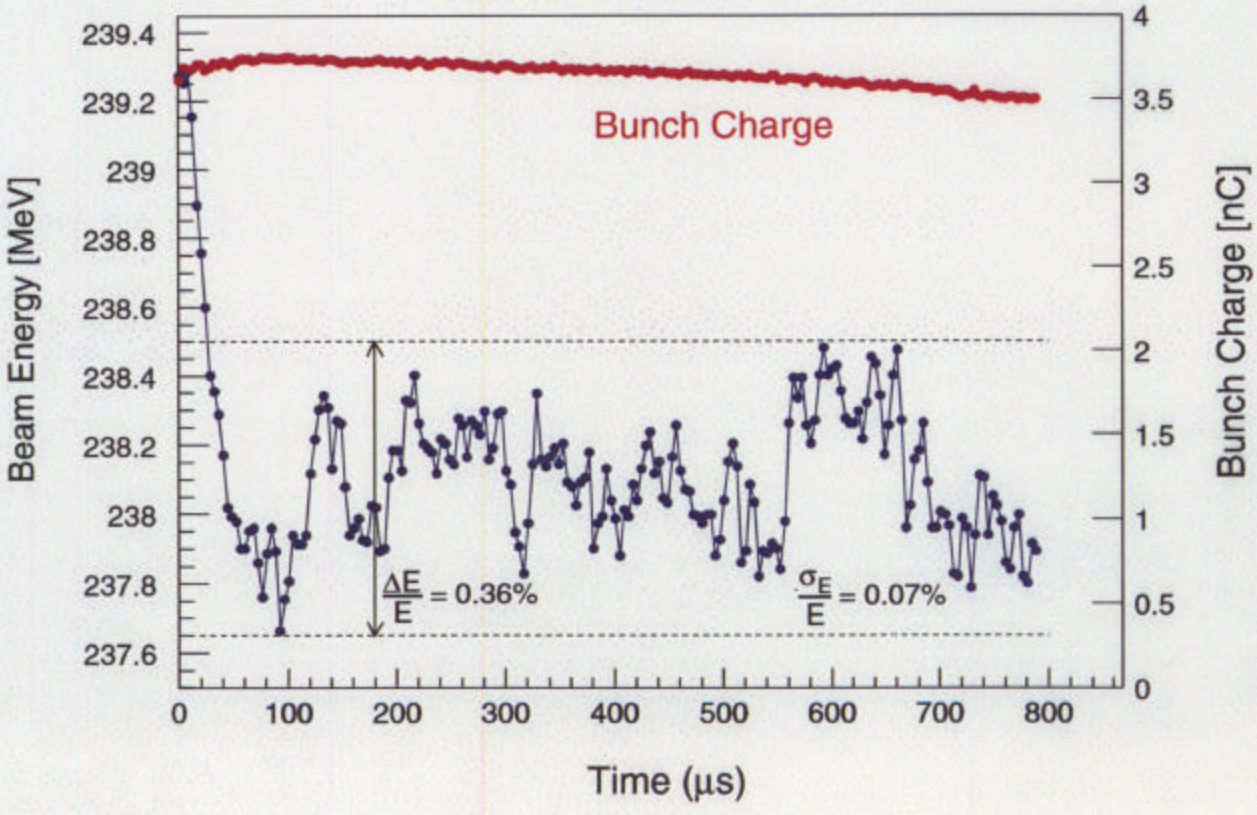


- Made with Solid, Pure Niobium (Weak Flux Pinning)
- Nb Sheets are Deep-Drawn to Make Cups, Which are E-Beam Wielded to Form Cavities.
- Cavity Limited to Nine Cells (1 m Long) to Reduce Trapped Modes, Input Coupler Power Losses and Sensitivity to Frequency Errors.
- Operated at 1.8-2 K in Superfluid He Bath (Surface Resistance Very Sensitive to Contaminates and Temperature: Increases 50 fold at 4.2 K). RF losses ($Q_0 \approx 10^{10}$) are $\approx$ 1 W/m.
- Q_{ext} ($\approx 3\times10^6$) Adjusted to Equal $Q_0 \times$ Gradient / (I $\times$ Rs). In Steady State, Essentially 100% of the 230 kW Input Power Goes to the Beam.

Beam Loading Compensation in TESLA

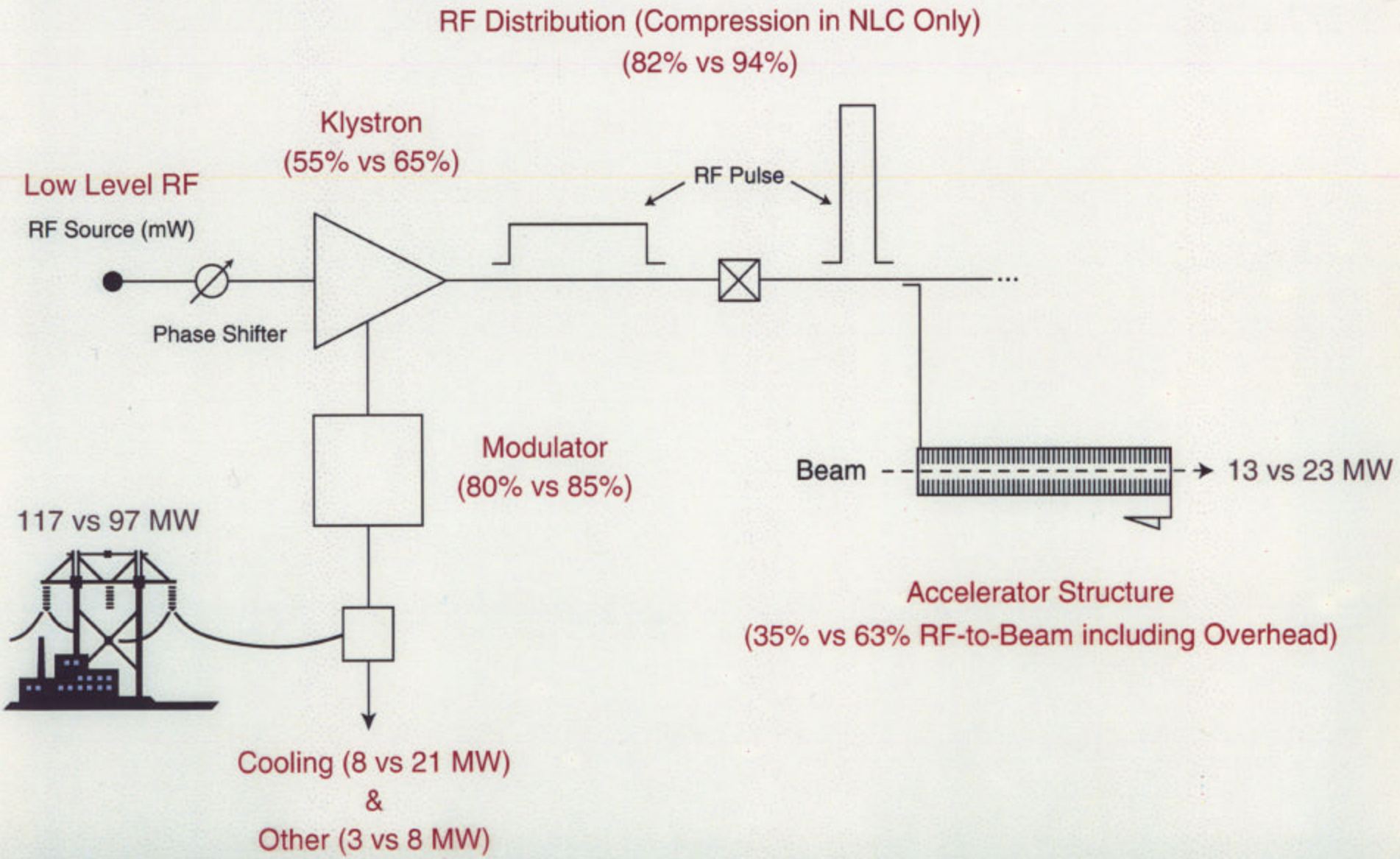


Telsa Test Facility (TTF) Beam Loading Measurements



Simplified RF System Layout

(NLC vs TESLA Efficiencies and Average Power)



NLC Linac RF Unit

Low Level RF System

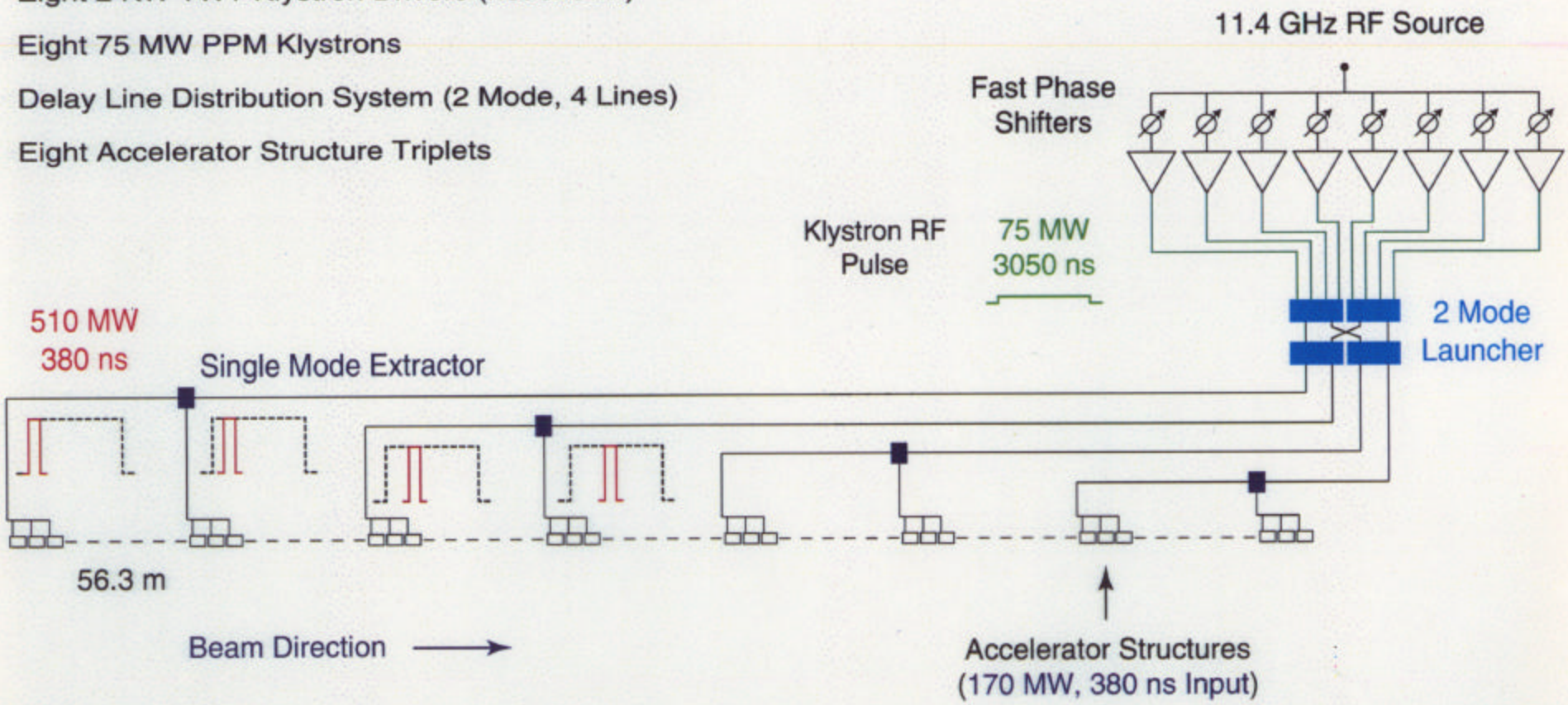
One 490 kV 3-Turn Induction Modulator (not shown)

Eight 2 KW TWT Klystron Drivers (not shown)

Eight 75 MW PPM Klystrons

Delay Line Distribution System (2 Mode, 4 Lines)

Eight Accelerator Structure Triplets

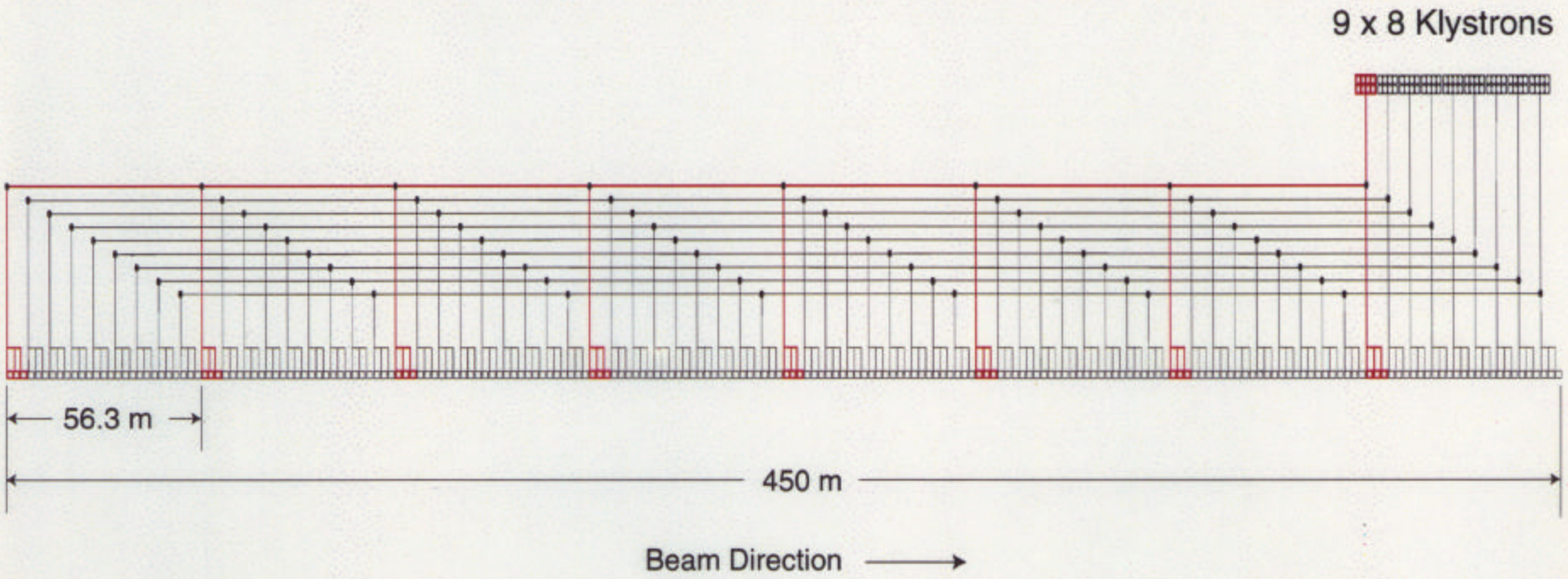


LINAC SECTOR

Delay Line Distribution System (DLDS) NONET

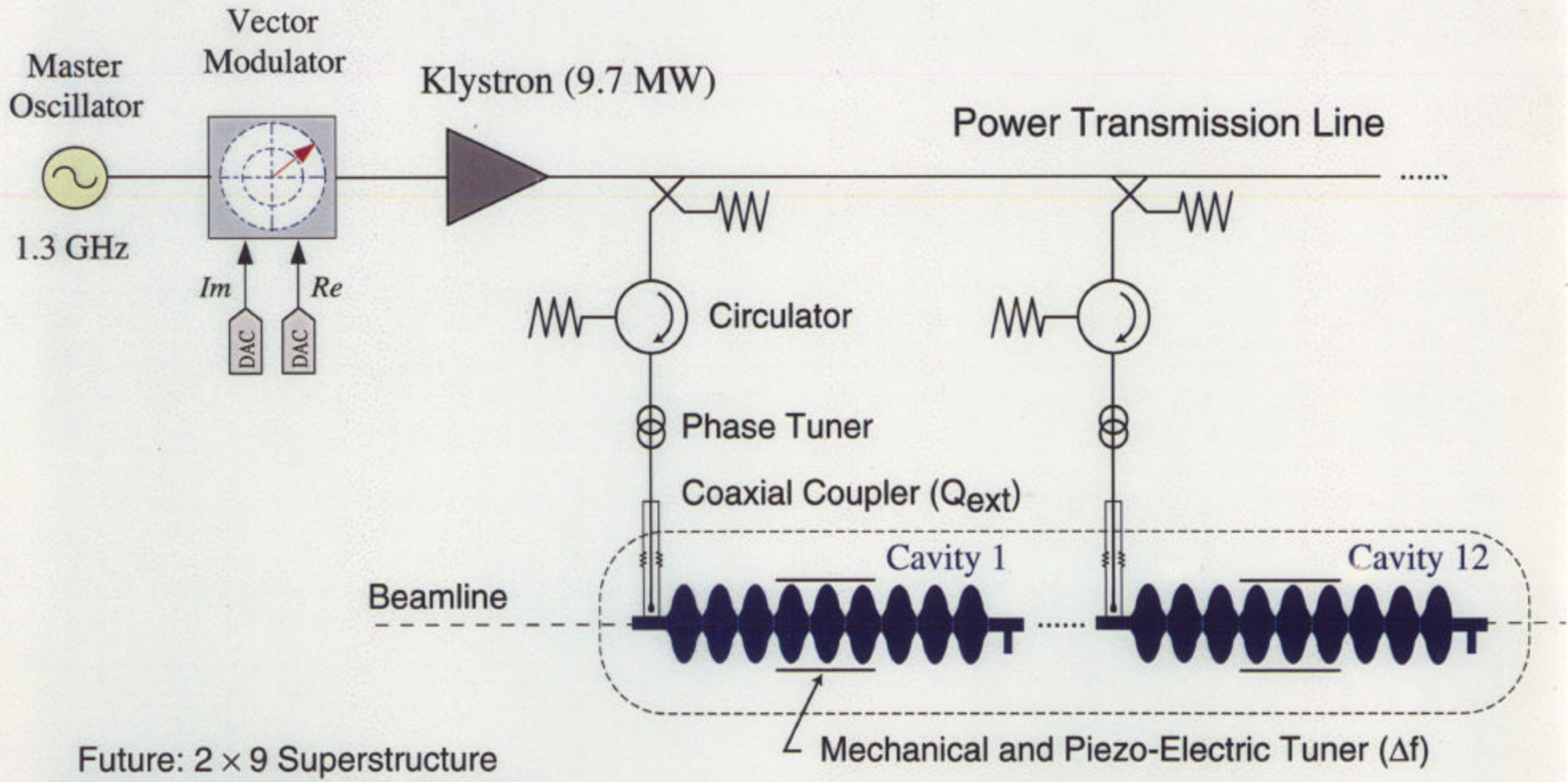
9 x 24 Accelerator Structures

Active / Actual Length = 9 x 24 x 1.8 / 450 = 86.3%

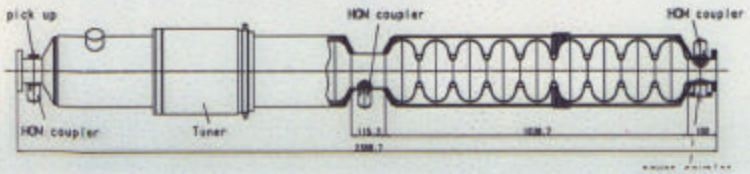


TESLA RF Station: One Klystron Feeds Three Cryomodules Each Containing Twelve, Nine-Cell Cavities

Length = 50 m, Filling Fraction with Quads = 75%

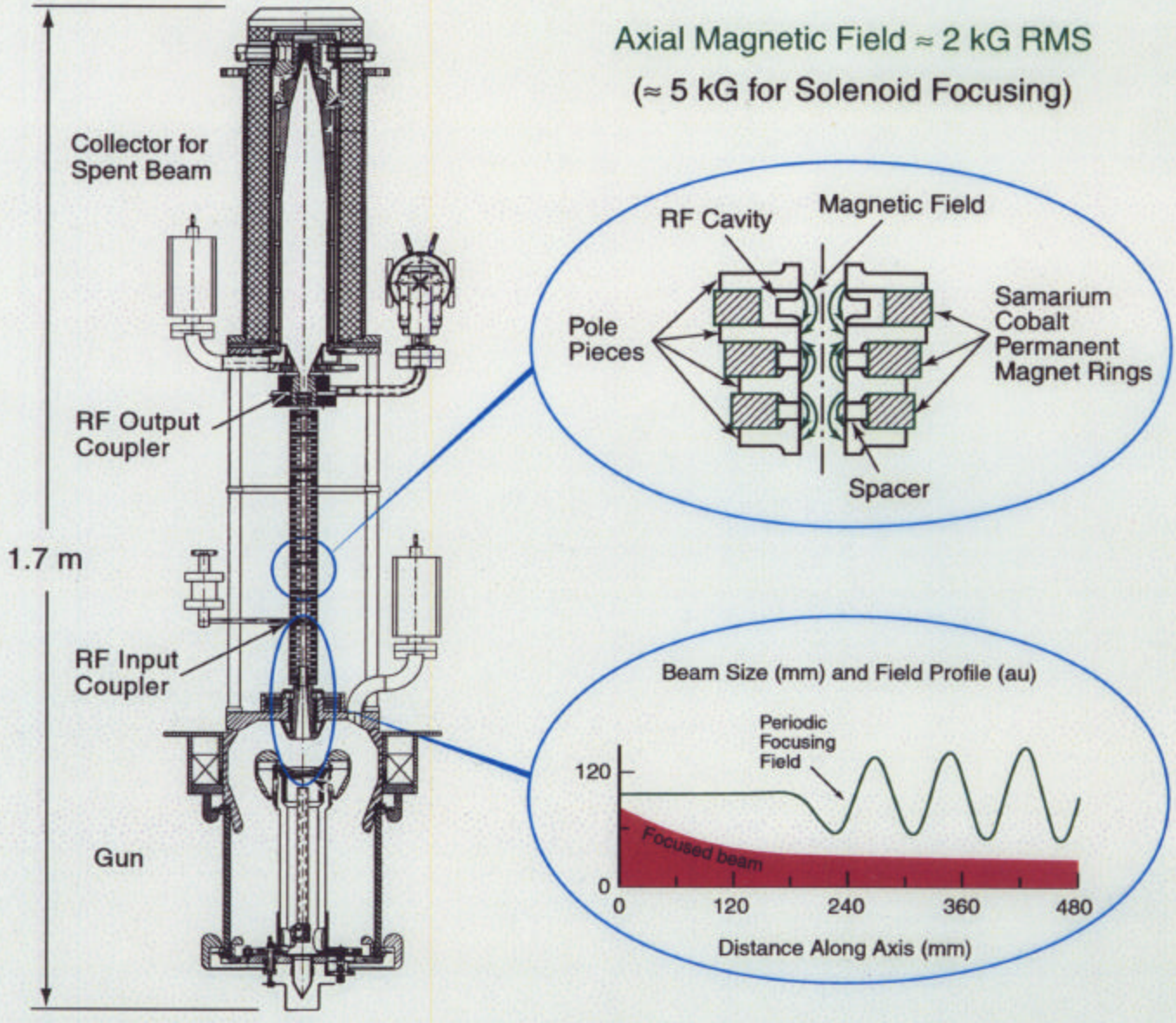


Future: 2 × 9 Superstructure
One Feed per Pair, 6 % Shorter



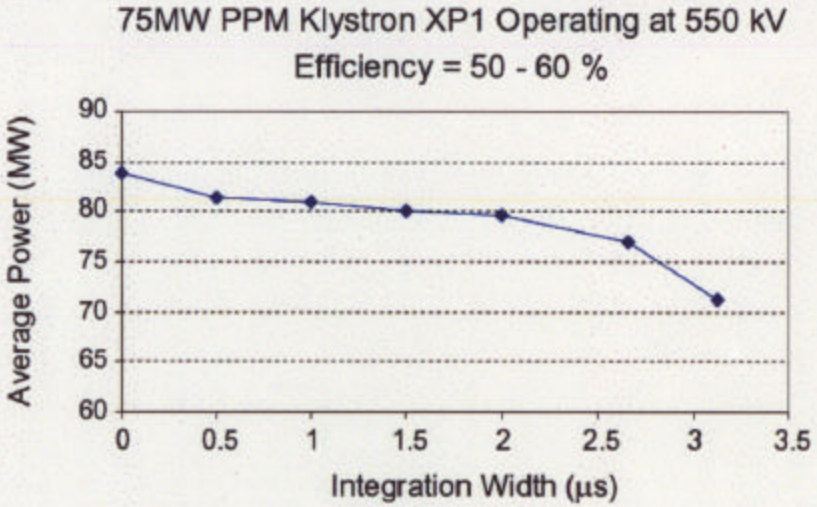
Cryomodule 1 of 3

Periodic Permanent Magnet (PPM) Focused X-Band (11.4 GHz) Klystron



SLAC 75 MW PPM Klystron Program

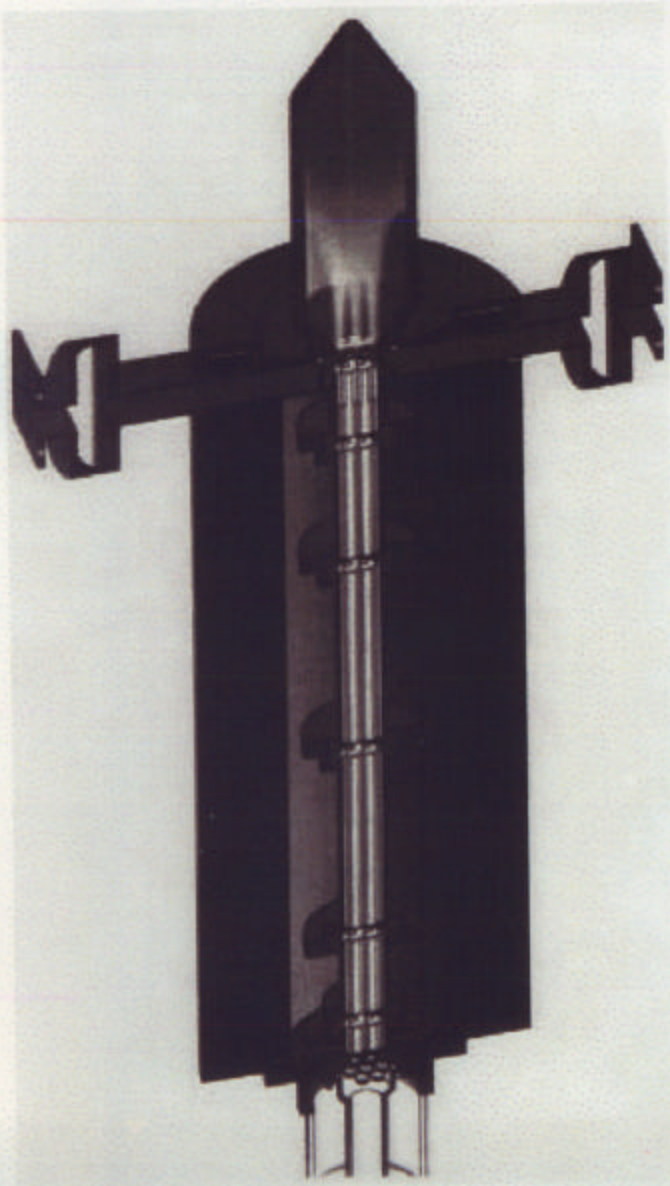
XP1: After a Number of Fixes, Achieved Stable Performance Over 70 MW at Twice the Design Pulse Length (3 μs, Which Was Modulator Limited)



XP3: Next Generation Tube Designed for Manufacturability

- Incorporate Lessons Learned from XP1
- Design Essentially Complete – Evaluating Cooling for 3 μs Operation
- Diode Version To Be Tested in March
- Klystron To Be Tested in July

TESLA Klystron Development



GOAL

Reduce HV Requirements
and Improve Efficiency
(Lower Space Charge)
with
Multiple Beam Klystron

Use Seven 18.6 A, 110 kV
Beams to Produce 10 MW
with a 70% Efficiency

Thomson TH1801
MultiBeam Klystron

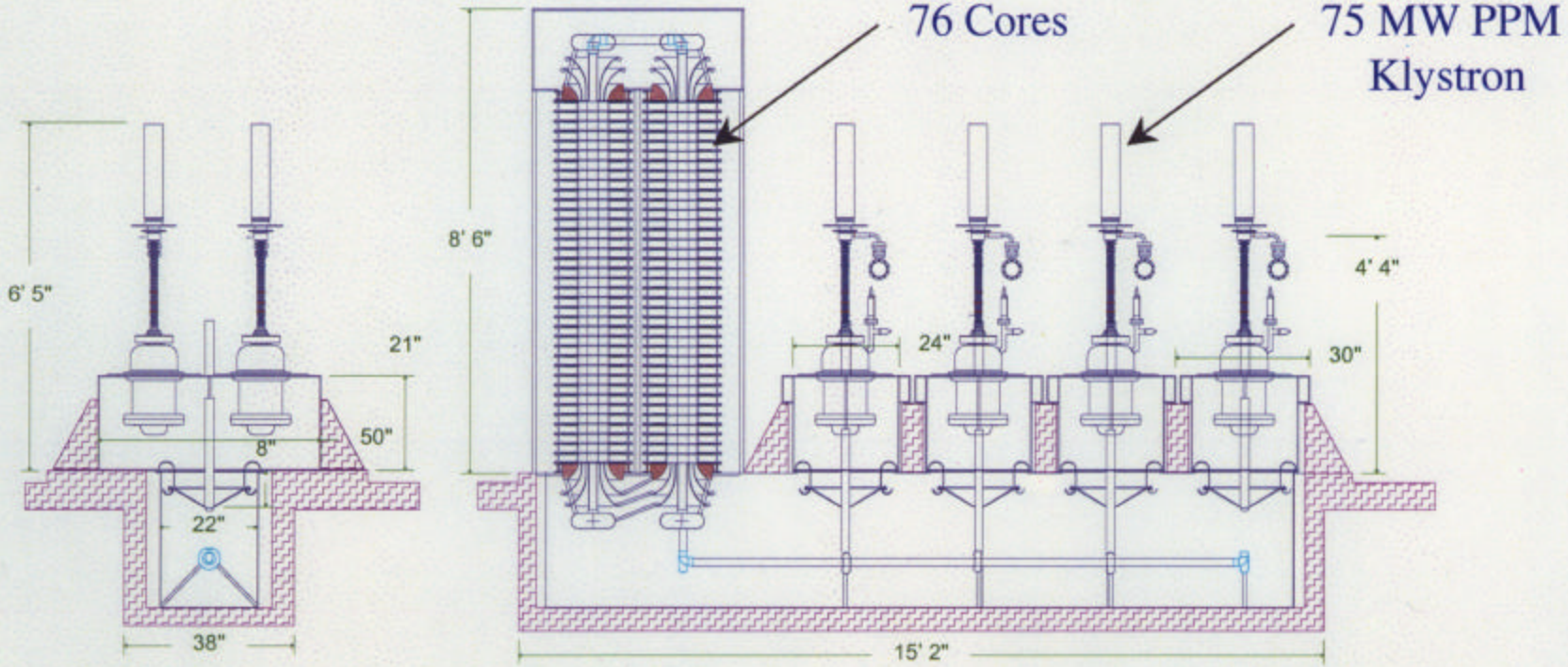
Spec's:
10 MW, 10 Hz, 1.5 ms
with 4 kW Solenoid Power

First Tube Achieved 65%
Efficiency at 1.5 ms, 5 Hz and
is Now Being Used in TTF

Photo of TH1801 Tube
(top) and Cathode (bottom

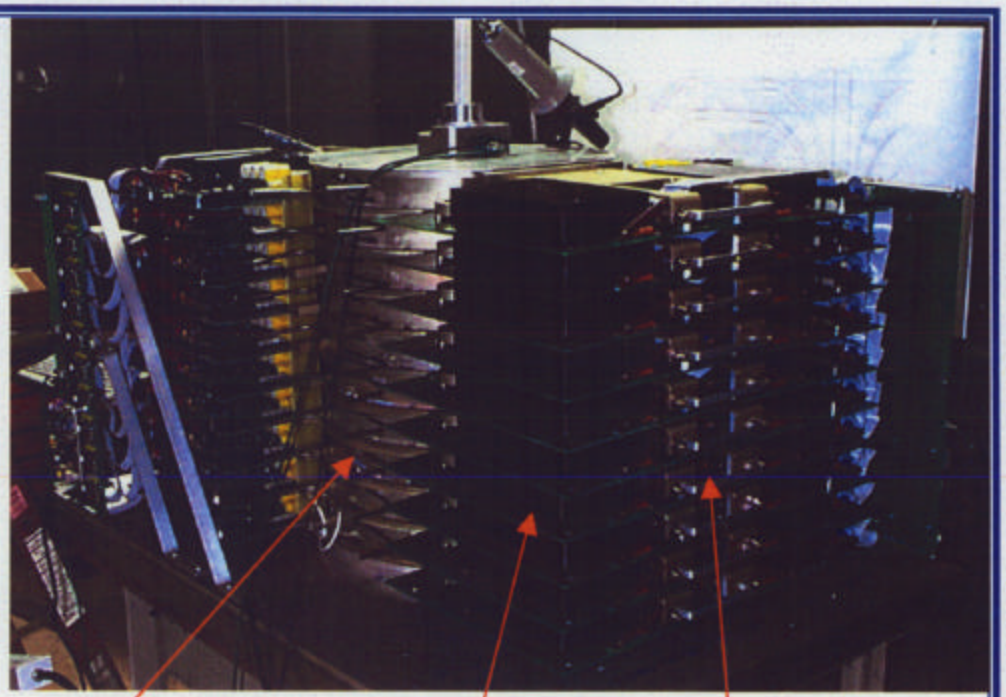
NLC Eight Klystron Induction Modulator

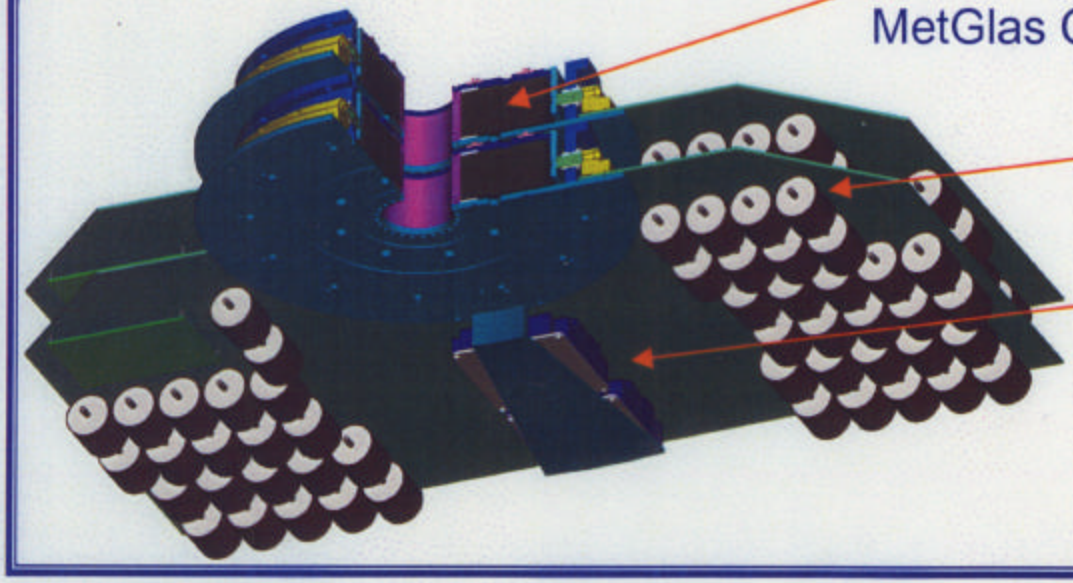
Drive 8 Klystrons with a 500 kV, 2 kA, 3 μs Pulse Generated from 76, 2.2 kV Induction Cores Summed Through a 3-Turn Secondary.



Induction Modulator
10 Core Test Setup

Generated 22 kV, 6 kA,
3 μs Pulses





MetGlas Cores

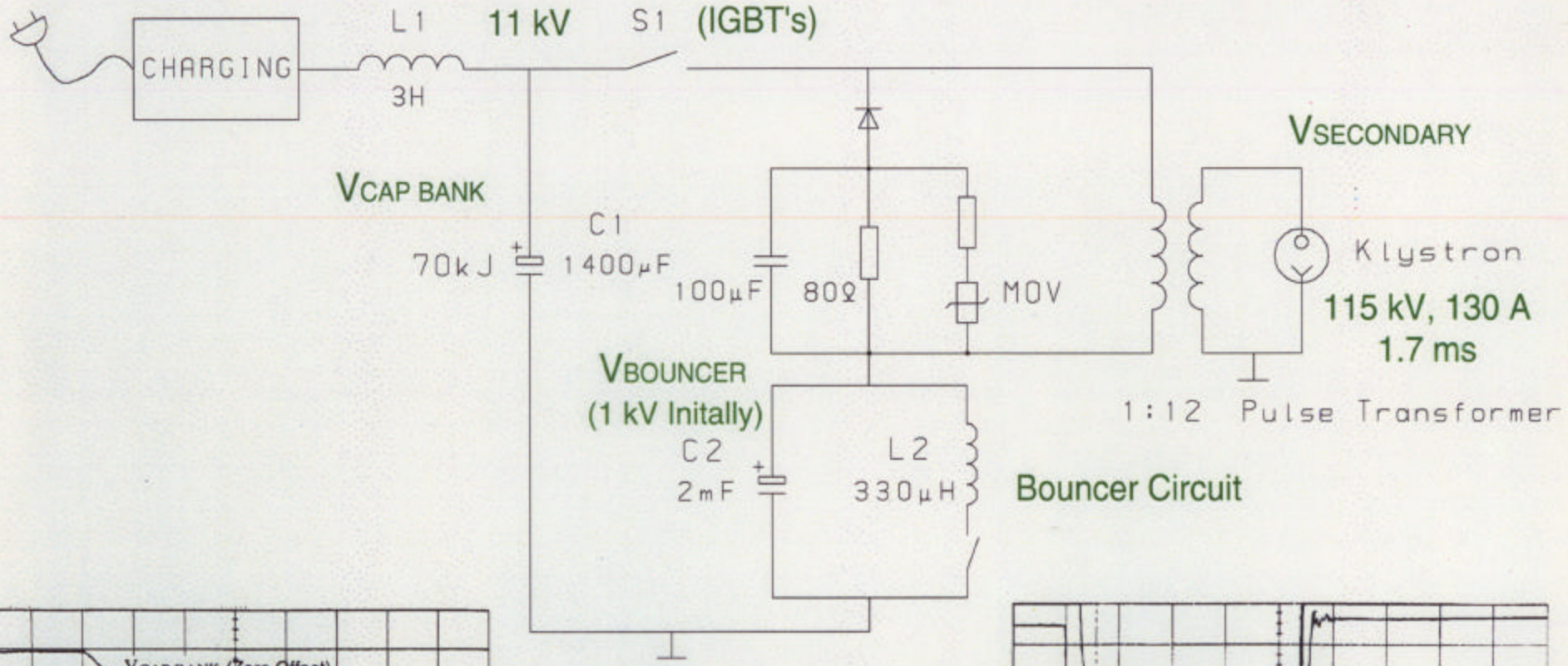
Capacitors

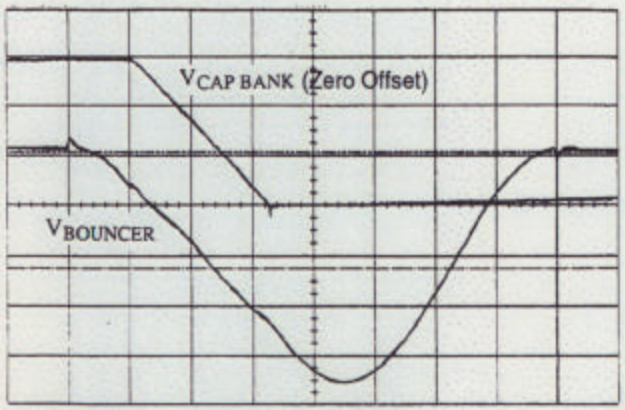
IGBTs

SLAC / LLNL / Bechtel NV

TESLA Modulator

Use FNAL Design in Which a Bouncer Circuit Offsets the Voltage Droop (19%) During Discharge of a Capacitor Bank

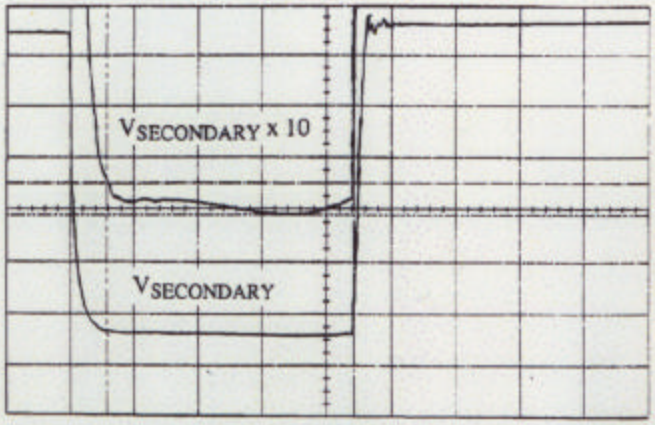




500 V/div

1 ms/div

2 kV/div (top)
20 kV/div (bottom)

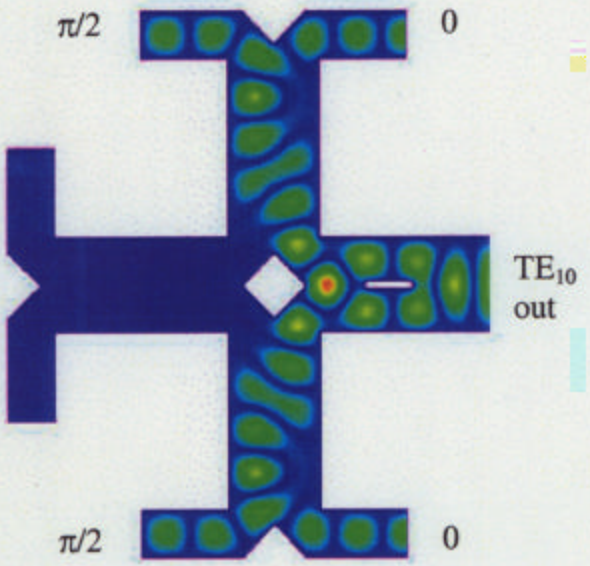


0.5 ms/div

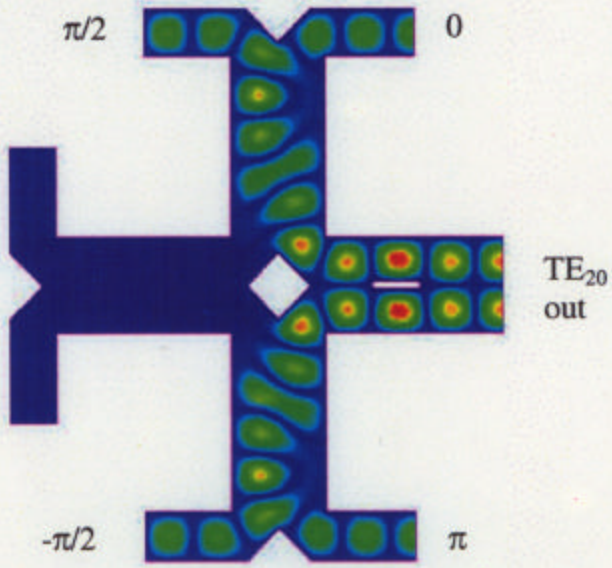
NLC RF Distribution

Switch Power Using a 'Cross Potent' Two-Mode Hybrid

Cold-Test Model with Cover Removed



a)



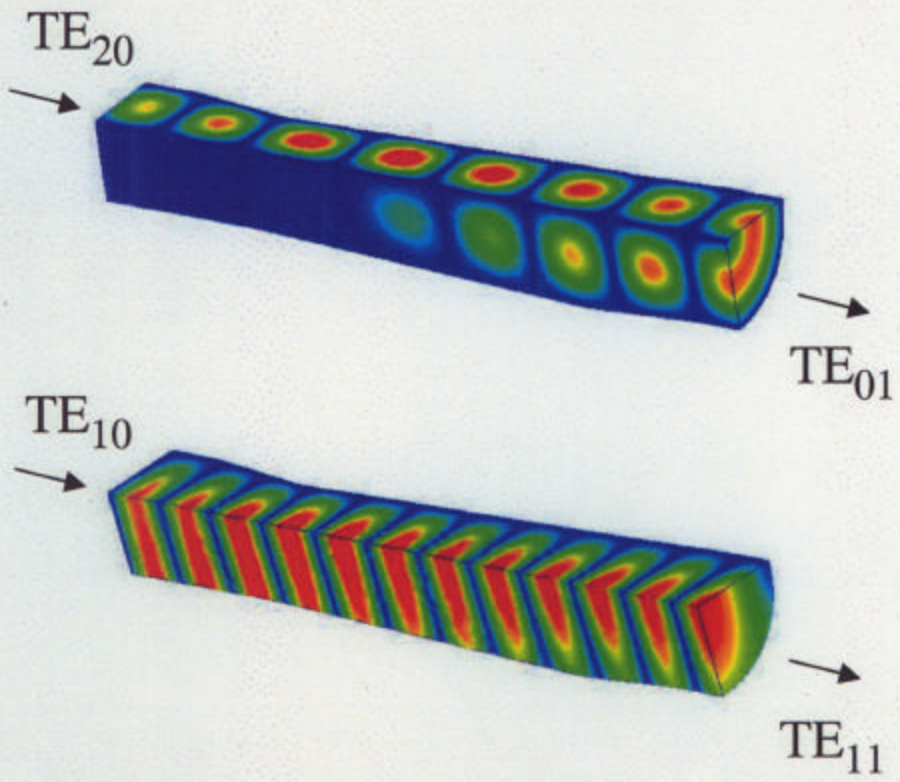
b)

Cross Potent operation with simulated electric field illustrating launching a) TE_{10} and b) TE_{20} in the right over-moded rectangular port with the indicated relative phases for four equal amplitude inputs. Alternate phases of the inputs sends the power to either of the left ports.

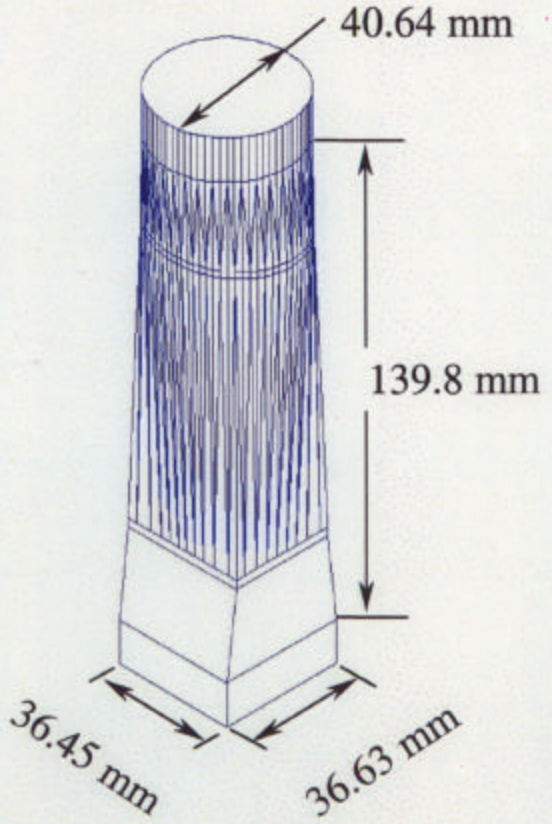
Rectangular-to-Circular Mode Converter

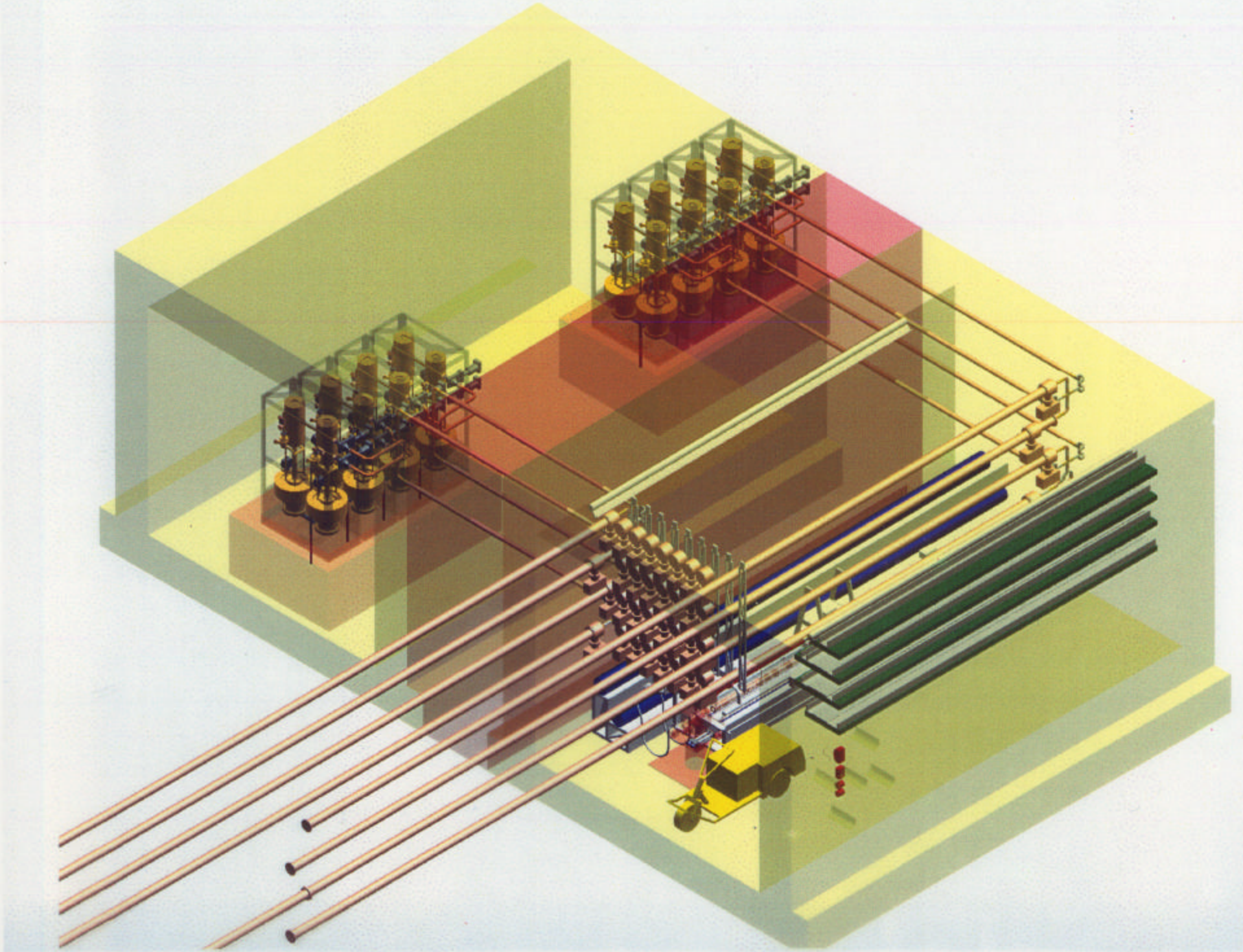
Convert to Low-Loss Circular WG Modes to Transport Power Hundreds of Meters

Electric Field Patterns

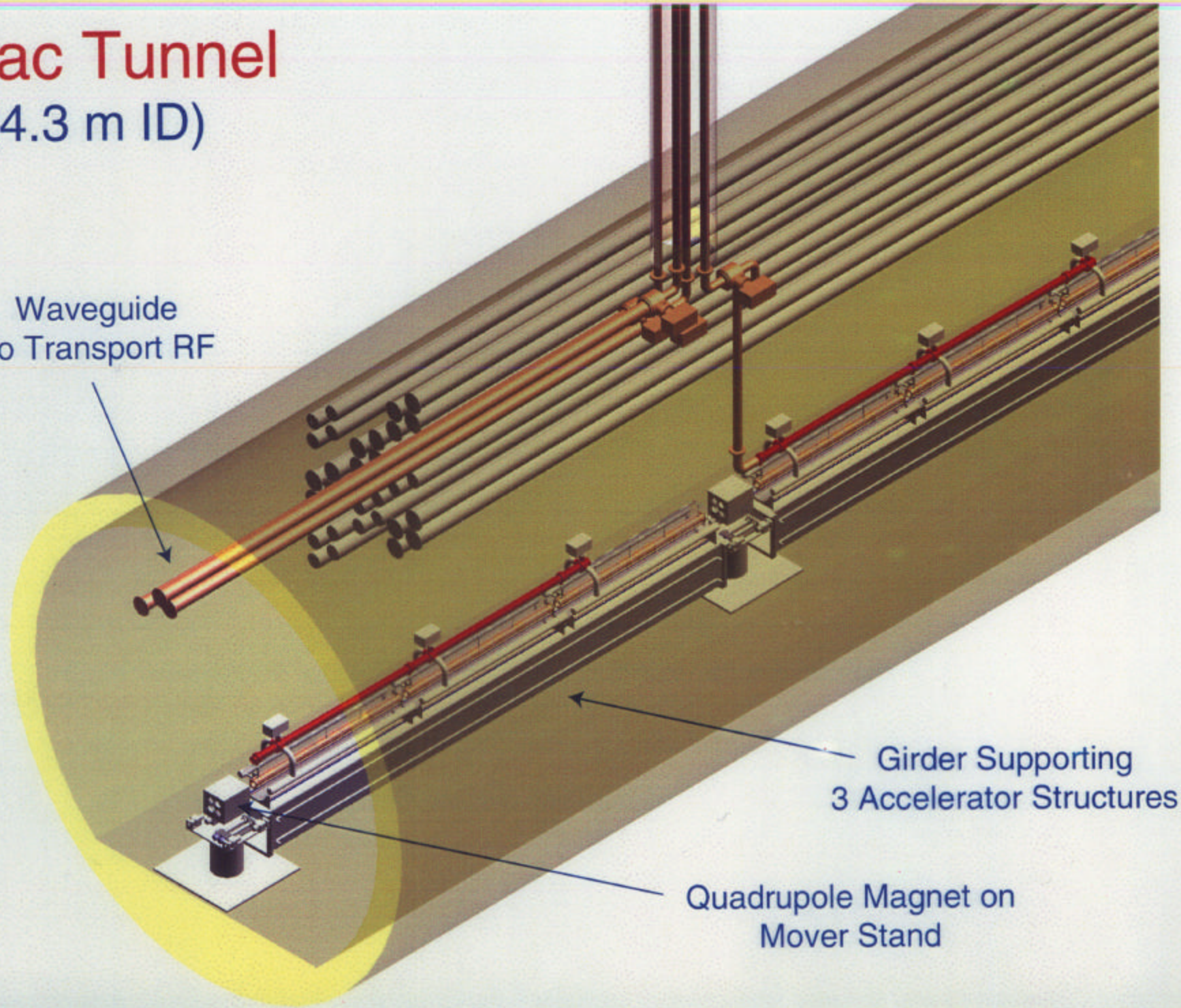


Converter Geometry

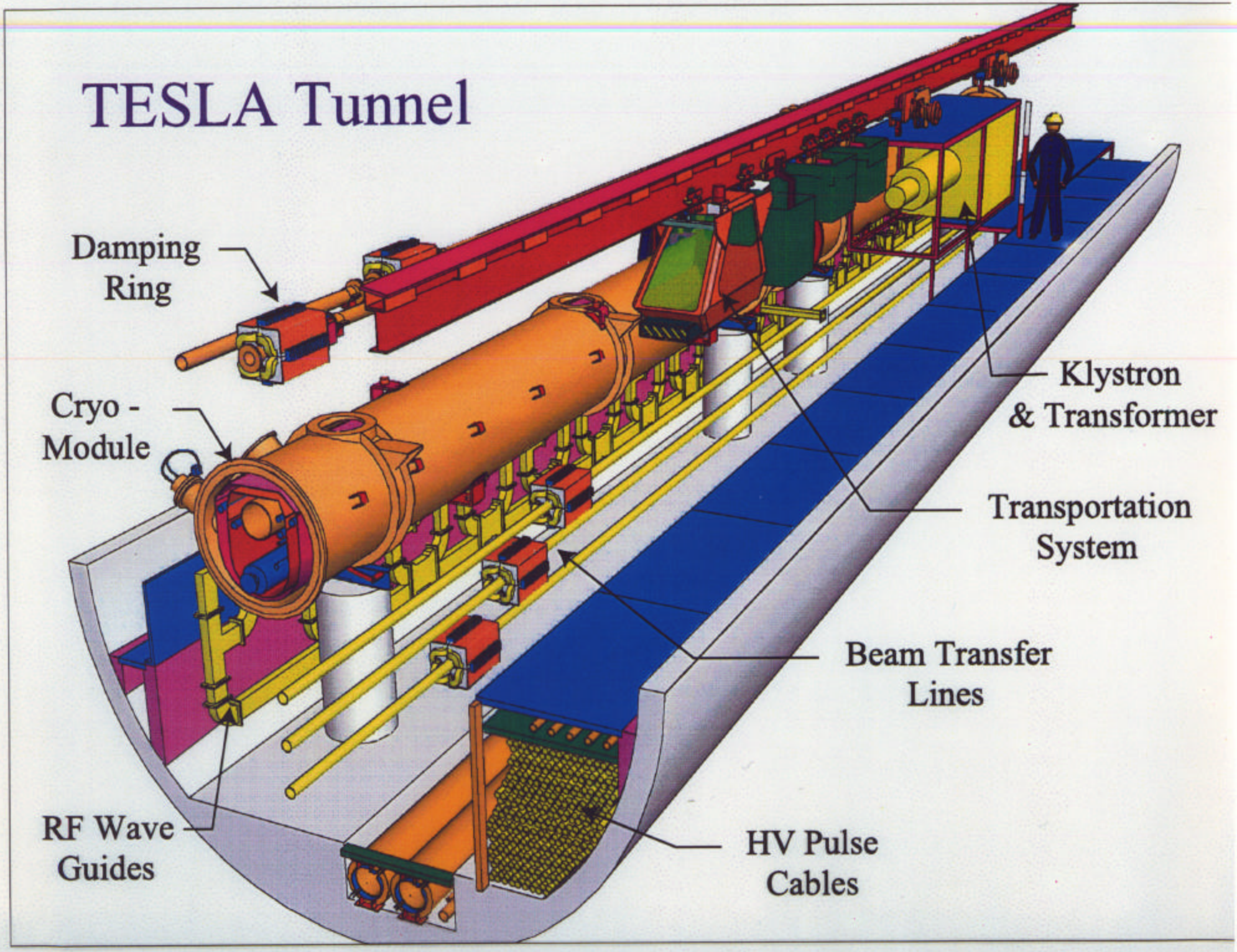




Linac Tunnel
(4.3 m ID)



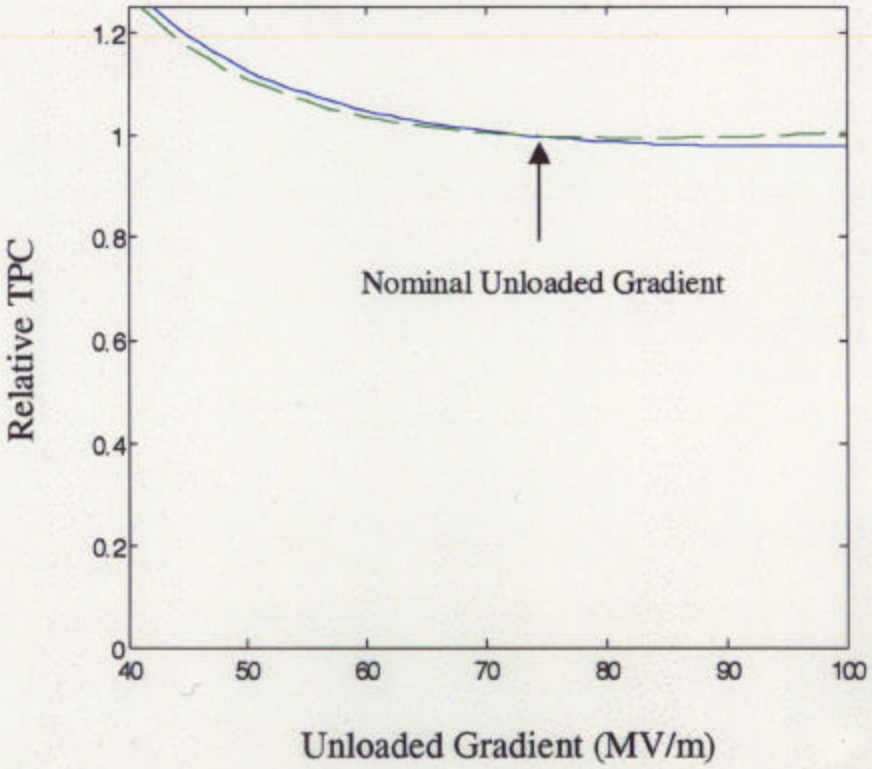
TESLA Tunnel



Linac Costs

- Linac Costs Do Not Dominate Total Project Cost (TPC).
  - NLC Linac (Including Tunnel) Accounts for about 45% of the TPC.
- Increasing the Accelerator Gradient (G) Does Not Necessarily Yield Lower Costs:
  - Power Costs Scale Roughly as G
    - ✓ AC Distribution
    - ✓ Klystrons
    - ✓ Modulators
    - ✓ RF Distribution
  - Length Costs Scale Roughly as 1/G
    - ✓ Structures and Supports
    - ✓ Magnets
    - ✓ Tunnel

Relative TPC –vs– Linac Unloaded Gradient for 1/2 TeV (solid) and 1 TeV (dashed) CMS

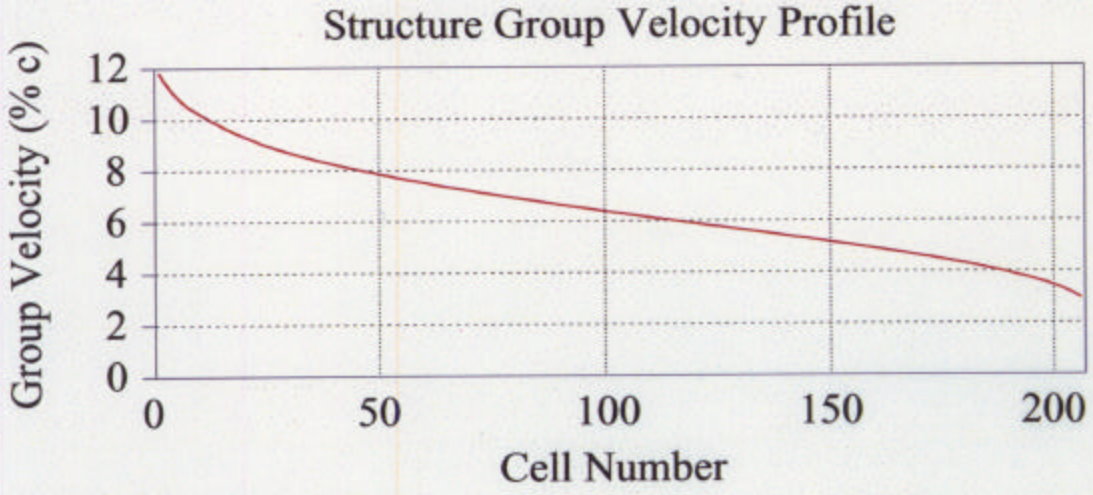


Transmission Line Model of Breakdown Damage

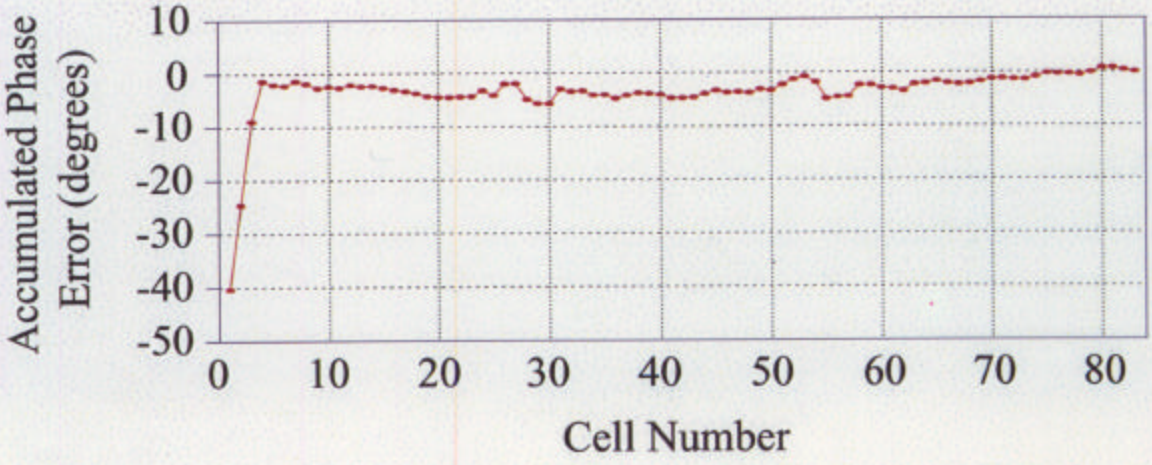
If Breakdown is Modeled as a Load Impedance,
Power Absorbed in the Load Scales as

$$\frac{v_g^2}{(R/Q)^2}\ \frac{\sin(\phi)}{\phi\sin(\phi) + 2\,v_g\cos(\phi)}\ \text{Gradient}^2$$

where v_g = Group Velocity/c R = Shunt Impedance
Q = Quality Factor ϕ = Phase Advance

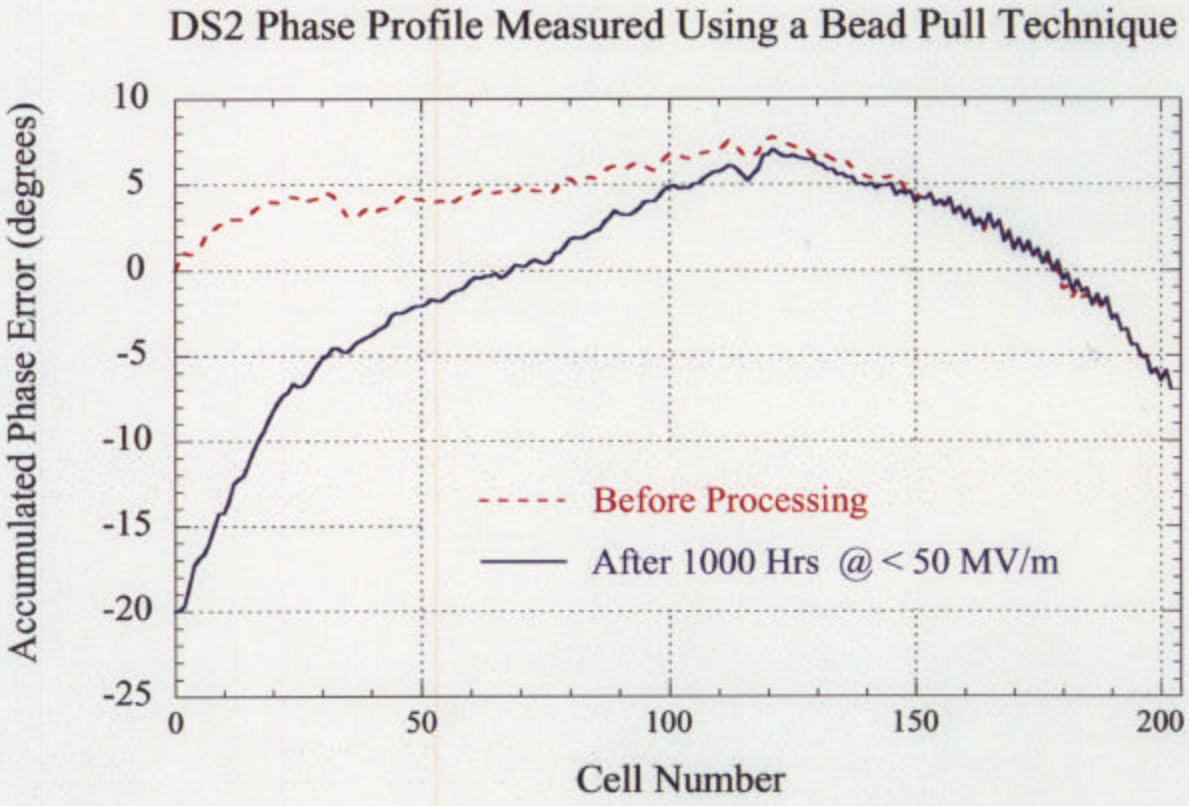


Phase Profile of an Early Constant Impedance Structure (v_g = 4.8 %)
after Processing to 90 MV/m Max, 79 MV/m Average



Effect of High Gradient Operation on the 1.8 m X-Band Accelerator Structures

- Example of a Change in the Structure Phase Advance Profile



- Summary of the Structure Phase Changes

Structure	Hours Operated	Max Grad. (MV/m)	Phase Change (deg.)	# Cells Affected
M2	440	85	25	70
DS1	550	54	7	80
DDS2	550	54	8	100
DS2	1000	50	20	150
DDS1	2700	73	90	120

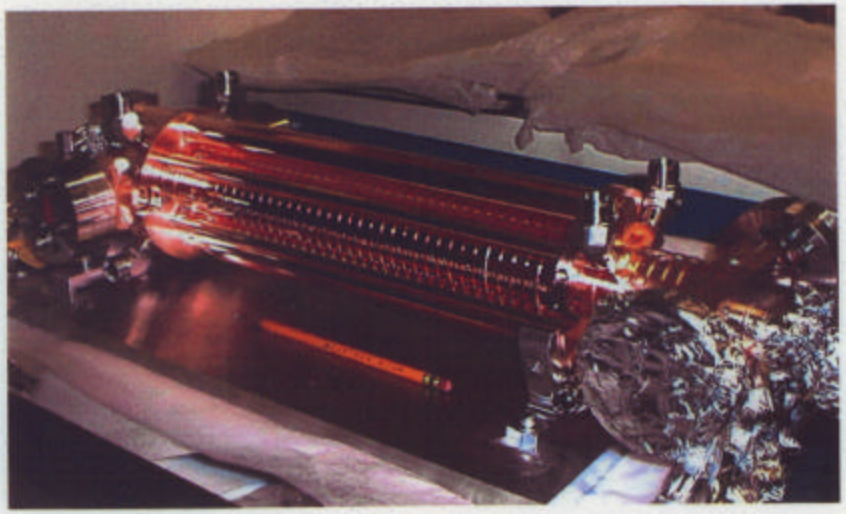
Multi-Prong Approach to Understanding High Gradient Limit

- Structure Parameters
  - Compare Performance of Traveling Wave Structures with Different
    - ✓ Initial Group Velocity (5 % and 3%)
    - ✓ Lengths (20, 50 and 100 cm)
  - Test 15 Cell Standing Wave Cavity
- RF Processing Program
  - 'Gentler' Processing of a Standard 12 % Group Velocity Structure
    - ✓ So Far Achieved 45 MV/m with Essentially no Damage
  - Systematic Study of Breakdown Events (Measure RF, Light, Sound, X-Rays and Currents) in Structures and Test Cells
- Materials and Handling
  - Surface Cleanliness/Damage Measurements with SEM and Auger
  - Test Different Cleaning Techniques
    - ✓ Ultra Pure Water Rinsing
    - ✓ Glow Discharge Cleaning
    - ✓ High Pressure Water Rinsing

Summary of First Low Group Velocity Structure (DS2S) Operation

DS2S:

- Last 52 Cells of a 206 Cell, 1.8 m Long Structure
- Group Velocity Varies from 5% to 3% c

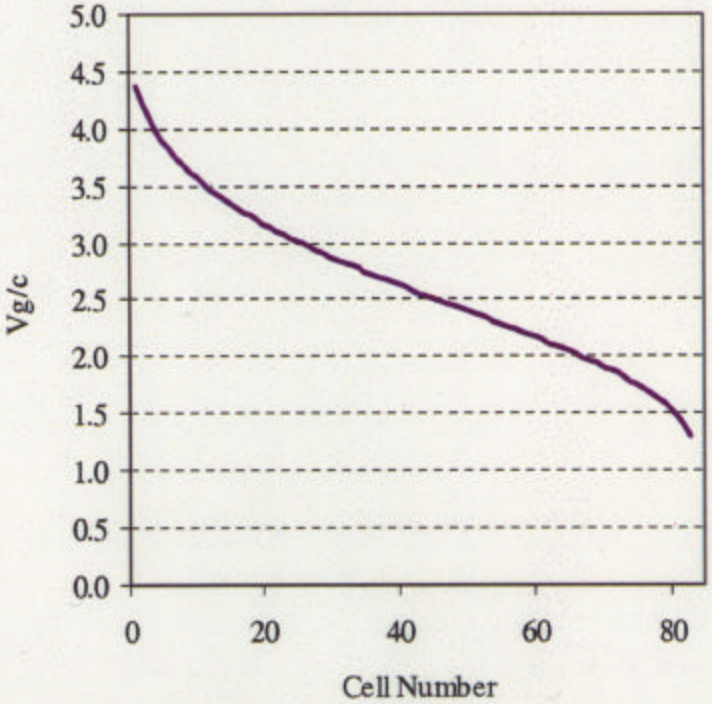


Results:

- Operated with 250 ns pulses at 60 Hz for 1500 hrs at gradients up to 73 MV/m.
- Measured about 5° phase shift early in run – did not increase with 500 hrs operation at 65 MV/m and 700 hrs at 70 MV/m.
- Trip rates at end of run:
  - ✓ 1 per hour at 70 MV/m.
  - ✓ 1 per 4 hours at 65 MV/m.

X-band Structure with $\Phi=150^0$/cell (120^0/cell)

- Lower Group Velocity: 4.4 → 1.3 % (11.8 → 3.0 %)
- Structure Length: 0.9 m (1.8 m)
- Cell Length: 10.9 mm (8.7 mm)
- Number of Cells: 83 (206)
- Structures per Girder: 6 (3)
- Input Power: 85 MW (170 MW)
- Unloaded Grad: 69.9 (72.4 MV/m)
- Es/Ea: 2.5 → 2.1 (3.0 → 2.2)



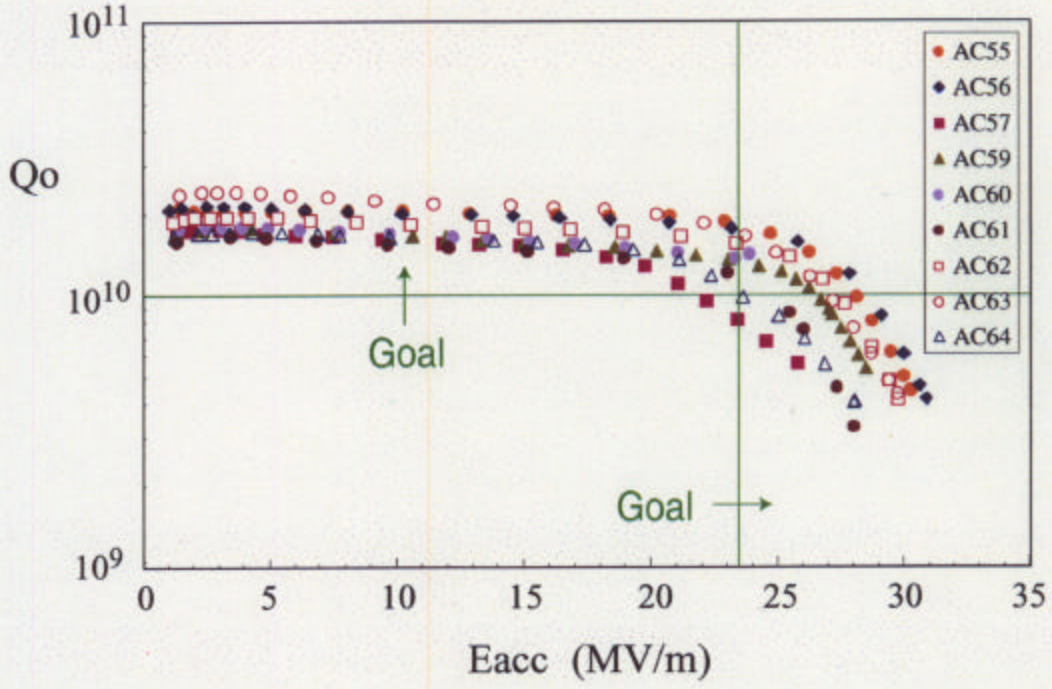
Cavity Fabrication And Treatment

Assembly of a string of eight, 9 cell cavities in the TTF clean room

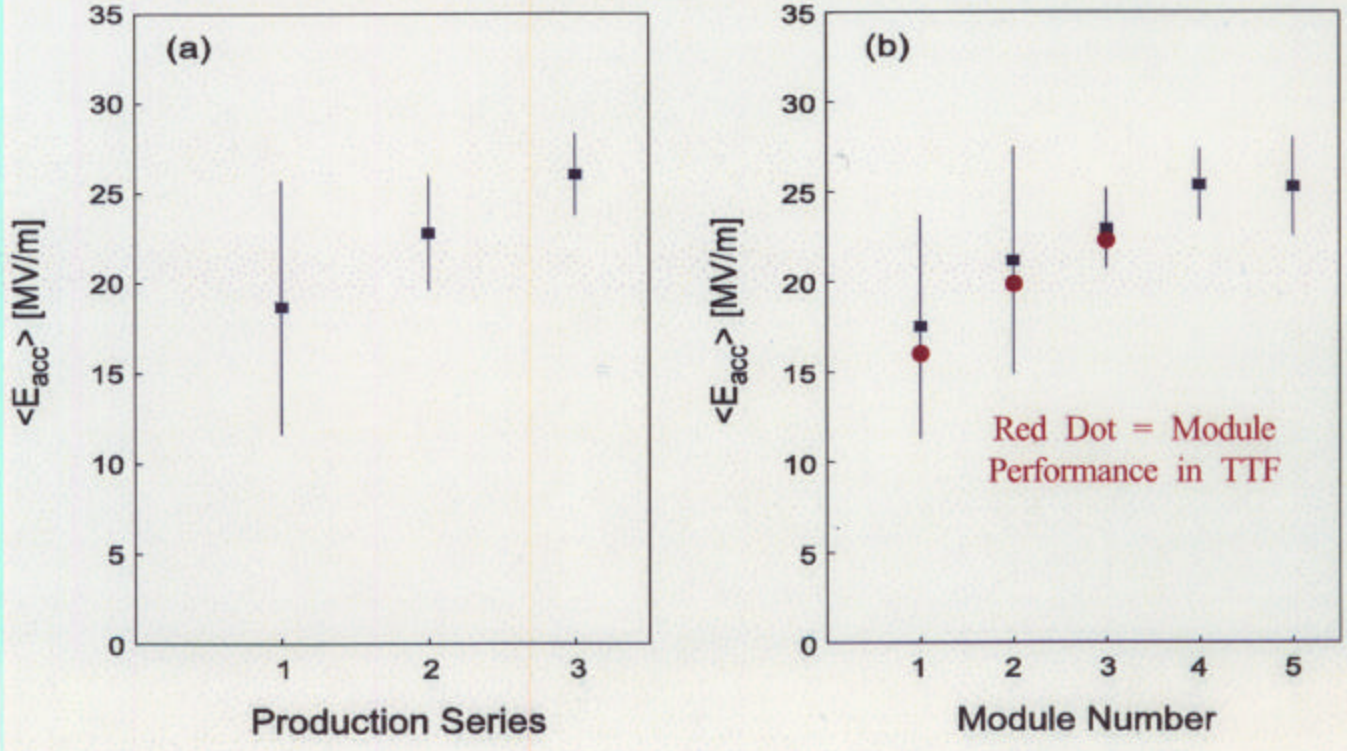
- Nb ingot outgassed (O, N, C reduced to ppm level), forged, rolled into 2.8 mm sheets, degreased, cleaned, annealed and eddy current scanned for cracks and inclusions.
- Cups are formed by deep drawing and then electron beam wielded to form cavities.
- Cavity inner surfaces etched with a mixture of HF, HNO_3, $H2PO_4$ (Buffered Chemical Polishing or BCP) to remove ≈ 80 μm layer of material, then rinsed with ultra-pure water and dried in a Class 100 clean room.
- Cavities annealed at 800 °C under UHV to remove the hydrogen and relieve mechanical stresses.
- Cavities outgassed at 1400 °C under UHV after thin (≈ 50 μm) Titanium layer is evaporated over the surface to act as an O_2 getter. Titanium removed with an 80 μm BCP.
- Cavities mechanically tuned to adjust resonant frequency and equalize field amplitudes in the nine cells.
- Cavities undergo light BCP followed by three stages of high pressure (100 bar) ultra pure water rinsing and then dried in a Class 10 clean room.
- Cavities powered with RF in a superfluid He bath cryostat.

High Gradient Performance

Excitation Curves Measured in the Vertical Cryostat for Cavities from the Third Production Series



Average Cavity Gradients at Qo ≥ 10^{10} Measured in the Vertical Cryostat for (a) the First Three Production Series and (b) Cavities Installed in the First Five Eight-Cavity Cryomodules



High Gradient Studies

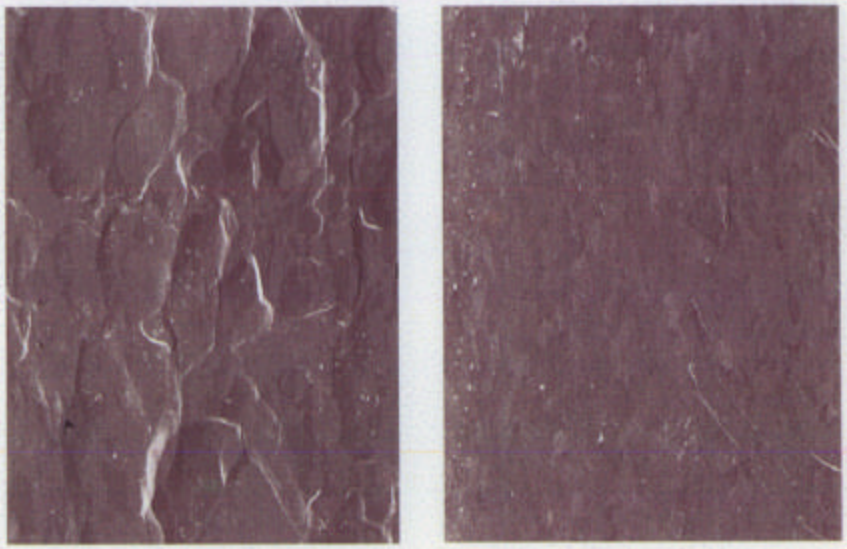
Results Using Electro-Polishing (EP) Technique Developed at KEK in which Material is Removed in an H_2SO_4, HF Mixture Under Current Flow

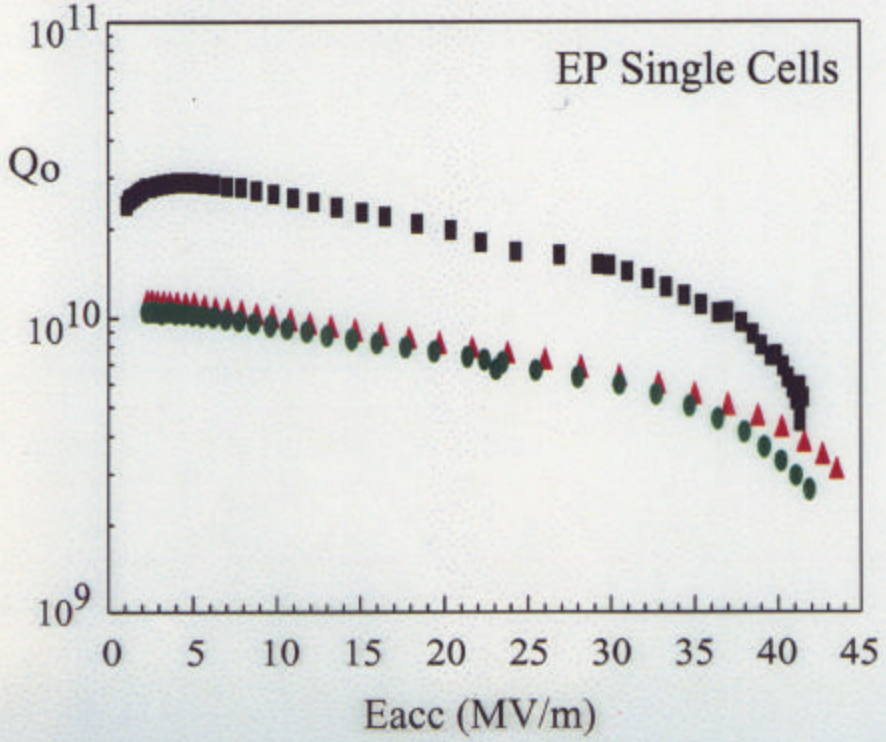
-vs-

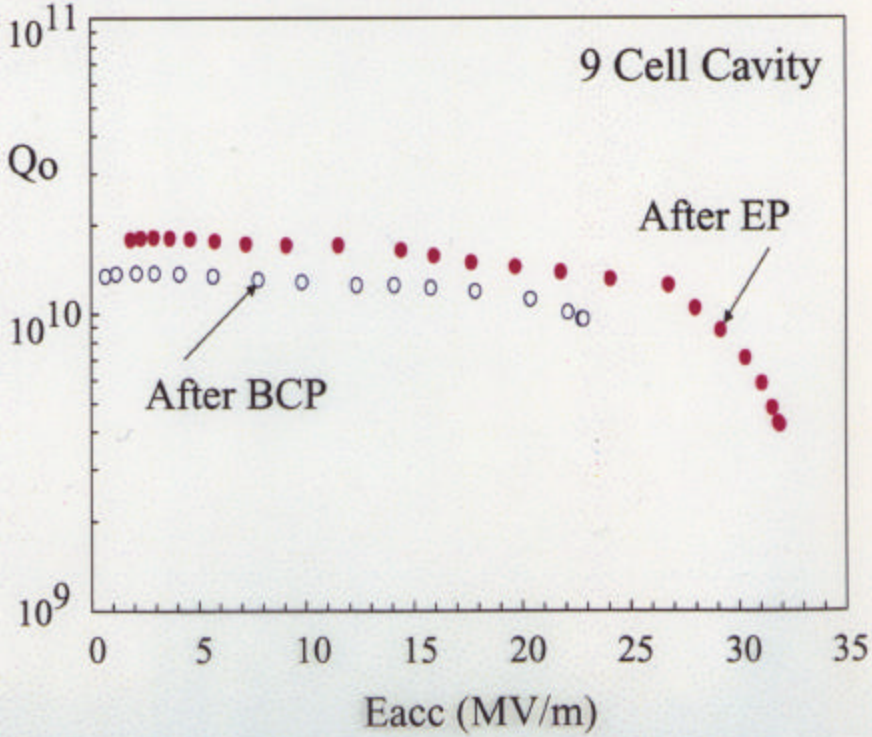
Buffered Chemical Polishing (BCP)

BCP Surface (1 μm Roughness)

EP Surface (0.1 μm Roughness)







Energy Upgrades

- NLC: 1000 GeV CMS
  - Tunnel Length (9.9 km) Stays the Same (Note, for Initial 500 GeV CMS Operation, Only Upstream ≈ Half Contains RF Components).
  - Running with Same Gradient and Beam Parameters as 500 GeV Operation Yields 890 GeV CMS: Lower Current to Reach 1 TeV.
  - Requires ≈ Doubling P_{AC} and RF System to Fill the Tunnel.
- TESLA: 800 GeV CMS
  - Tunnel Length (14.6 km) Stays the Same (Assumes 2×9 Superstructures Initially Installed).
  - Run at 35 MV/m with 34% Higher Beam Current and 50% Higher P_{beam}. (Gradient Limit from Superheating is 50-60 MV/m.)
  - Requires ≈ Doubling 2 °K Cooling Capacity ($Q_0 = 5\times10^9$) and Number of Klystrons and Modulators. P_{AC} Increases by 50%.