NLC - The Next Linear Collider Project

The NLC Design

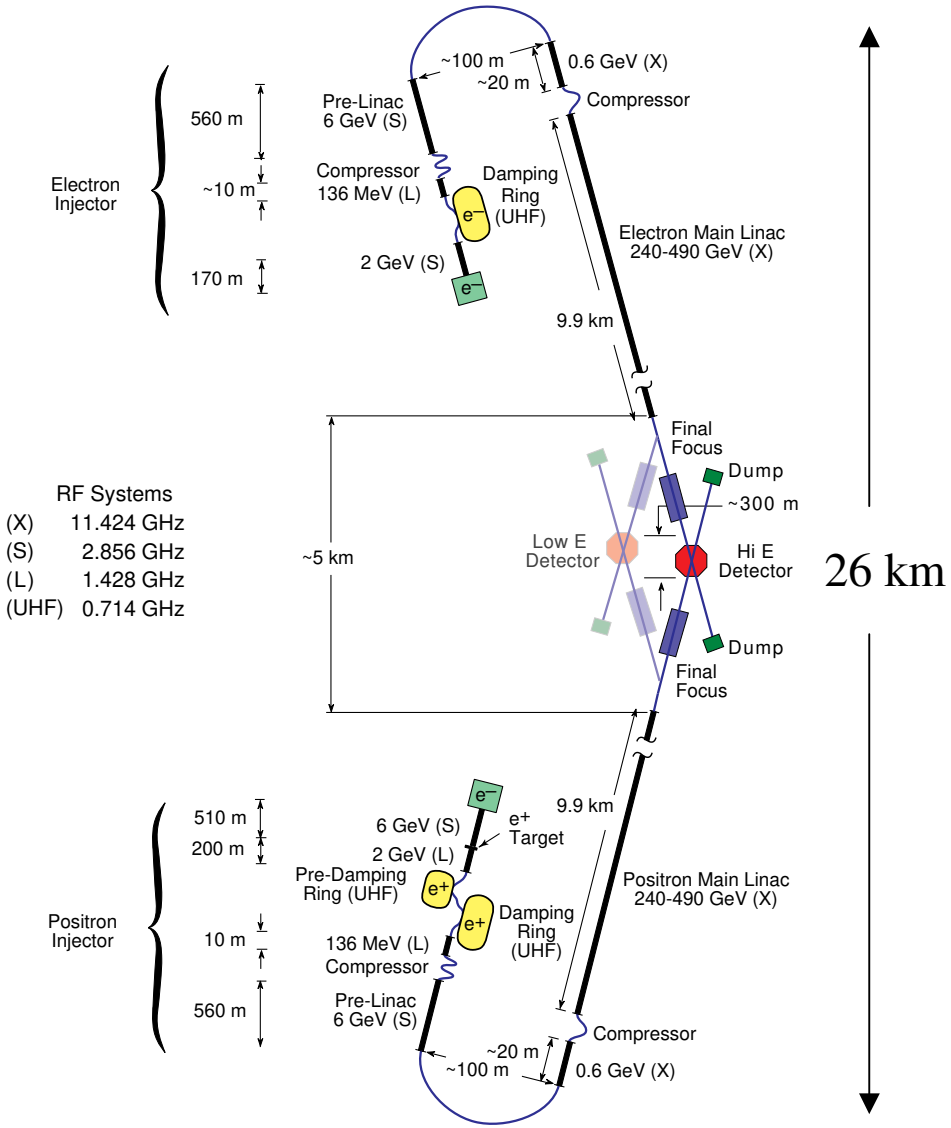
Linear Collider Workshop 2000

FNAL

October 24th, 2000

Tor Raubenheimer

NLC Design Changes



- Focused on cost reduction over last year – expect 30% reduction
- Many RF system improvements
- Facility length reduced by 20%
- Hi/Lo energy IR scheme and BDS redesign to optimize $\mathcal{L}$ and open future expansion possibilities
- Investigating 180 Hz operation
- Technology based on results from test facilities: FFTB, NLCTA, ASSET, KEK ATF and knowledge gained from SLC operation

NLC Project Scope

- Injector Systems — 1.5 TeV
- Main Linac — 0.5 - 1.0 TeV
  - Housing with all internal services
  - Half filled for initial 500 GeV cms
  - Upgrade by adding rf, water, power to the 2nd half of the tunnels

  (1.5 TeV with increased gradient or length)
- Beam Delivery (high energy IR) — 1.5 TeV
  - Two BDS tunnels and IR halls with services
  - some magnet strengths must be increased to get from 1 TeV to 1.5 TeV

  (length will support a 5 TeV FFS)

NLC Energy Evolution

Stage 1: Initial operation

500 GeV cms

$L = 5x10^{33} \rightarrow 20x10^{33} \Rightarrow 500\ fb^{-1}$

Stage 2: Add additional X-band rf components

1 TeV cms

$L = 20x10^{33} \rightarrow 30x10^{33} \Rightarrow 1000\ fb^{-1}$

Higher Energy Upgrades:

- 1.5 TeV with upgrade of linac rf system or length increase
  - injector and beam delivery built for 1.5 TeV
- 3 TeV+ with advanced rf system and upgraded injector
  - see CLIC parameters: "*A 3-TeV e+e- Linear Collider Based on CLIC Technology*," CERN-2000-008
  - beam delivery sized for 3 to 5 TeV collisions

NLC Progress

- Established collaborations with KEK, LBNL, LLNL, and FNAL
  - KEK focused on rf development
  - Berkeley concentrating on magnet design and damping ring issues
  - Livermore focusing on solid-state modulators and γ-γ IR
  - Fermilab taking responsibility for main linac beamline:
- Performed bottoms-up cost estimate for Lehman review
- Successful Lehman review $\rightarrow$ 8B$ project cost
- Have demonstrated most *necessary* rf hardware (NLC Test Accelerator) **however** the cost optimized hardware is still in development **and** rf power handling is still a question
- More aggressive rf design for lower cost and better efficiency
- Working on cost reduction throughout design: expect 30%

NLC RF System

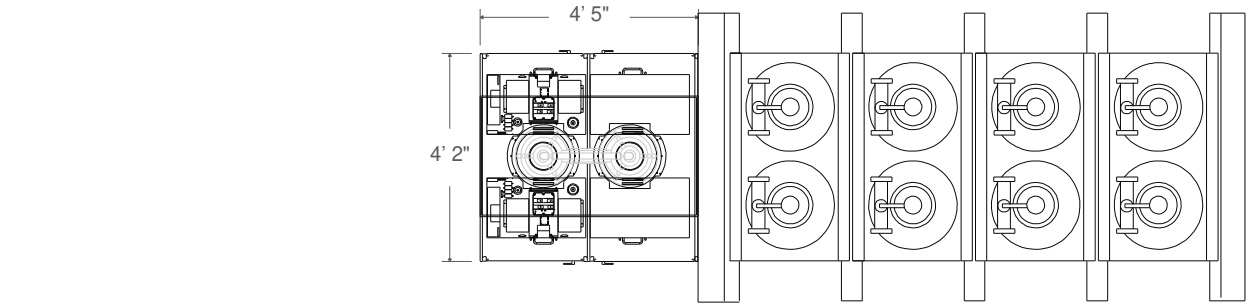
- RF system consists of 4 primary components:
  - Modulators: line ac → pulsed dc for klystrons (500 kV, 250 A)
  - Klystrons: dc pulse → 75MW at 11.424 GHz
  - RF Pulse Compression (DLDS): compresses rf pulse temporally, increasing the peak power, and delivers the power to the structures
  - Accelerator Structures (DDS & RDDS): designed to transfer power to the beam while preventing dipole mode driven instabilities
- Each linac has 100 modules consisting of 1 modulator, 8 klystrons, 1 DLDS system, and 24 accelerator structures
- Need good efficiency, reliability, and low cost!

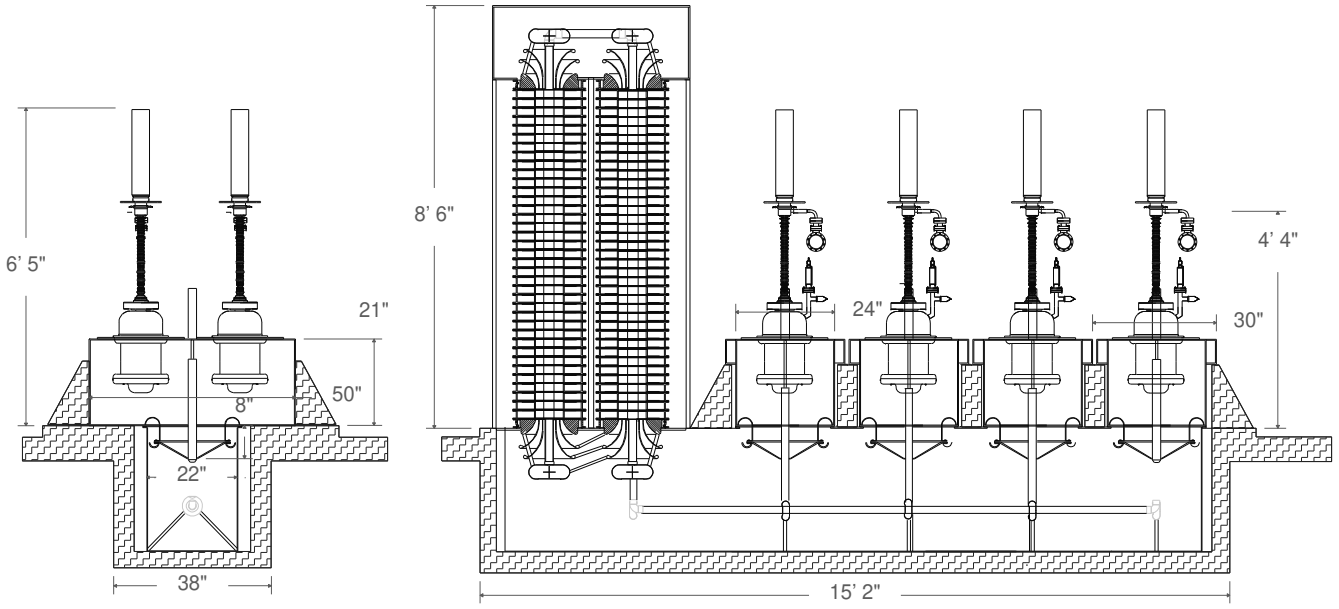
Solid-State Modulator

- Conventional modulators are expensive and inefficient with short pulses: ~ 60%
- Program at LLNL to develop ‘Induction Modulator’ based on solid-state IGBTs: efficiency ~ 80%
- IGBTs developed for e-trains with 2 to 3 kV and 3kA
- Drive 8 klystrons at once
- Full modulator finished this winter

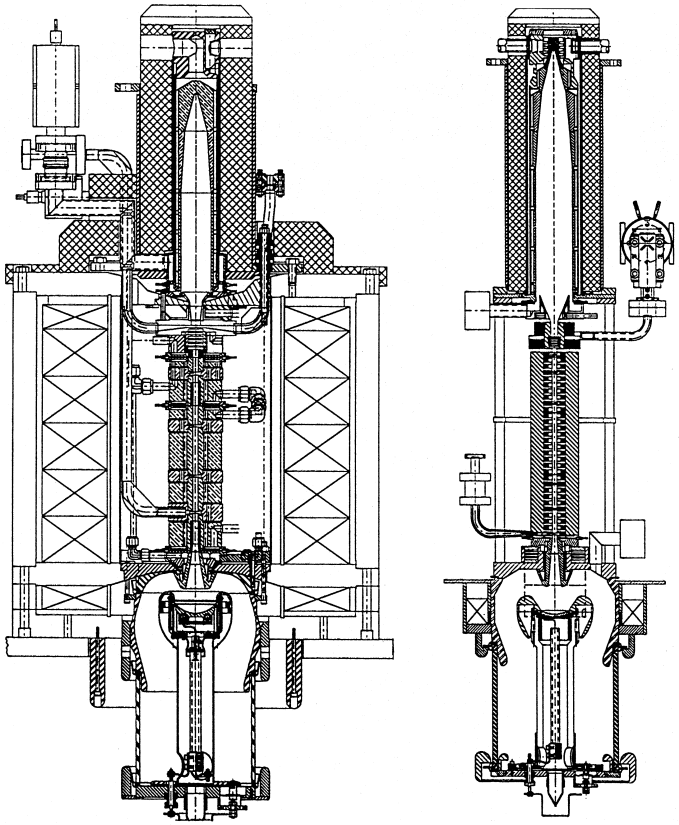
10 Core Test Stack

Solid State Modulator 8-pac





PPM Klystrons

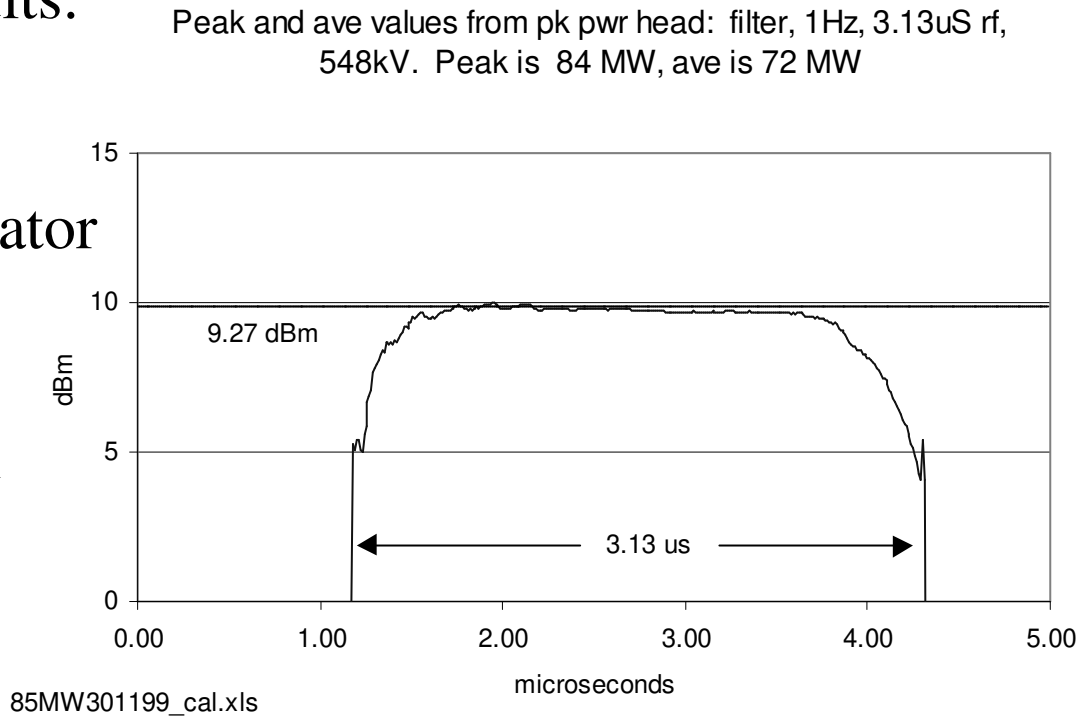


XP-1 75 MW Klystron

- XP-1 based on very successful 50 MW Periodic-Permanent Magnet (PPM) klystron but included many ‘simplifications’
- XP-1 testing results:

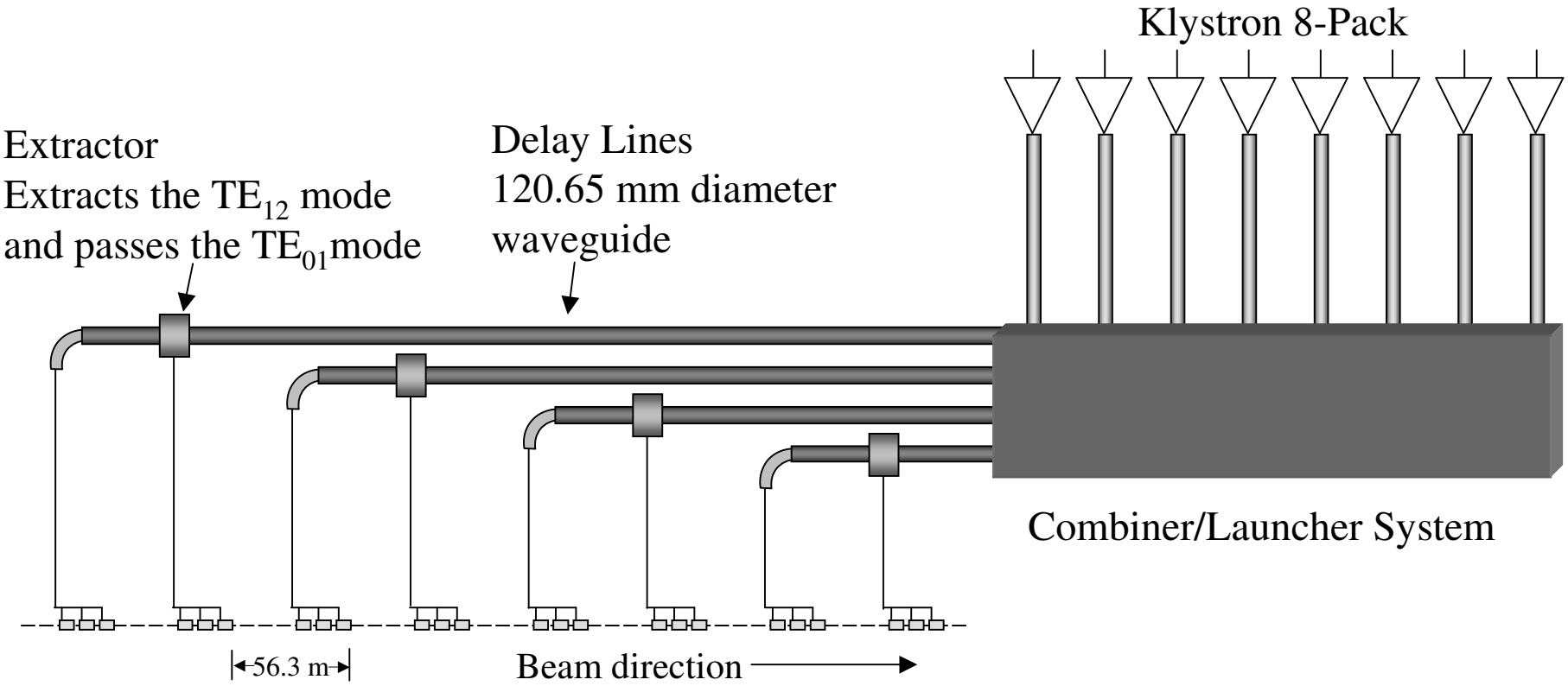
3us pulse length limited by modulator

average power 72 MW and peak power >80 MW



- Designing a second 75 MW tube with better field profile and features to improve manufacturing—to be tested this fall

DLDS Pulse Compression

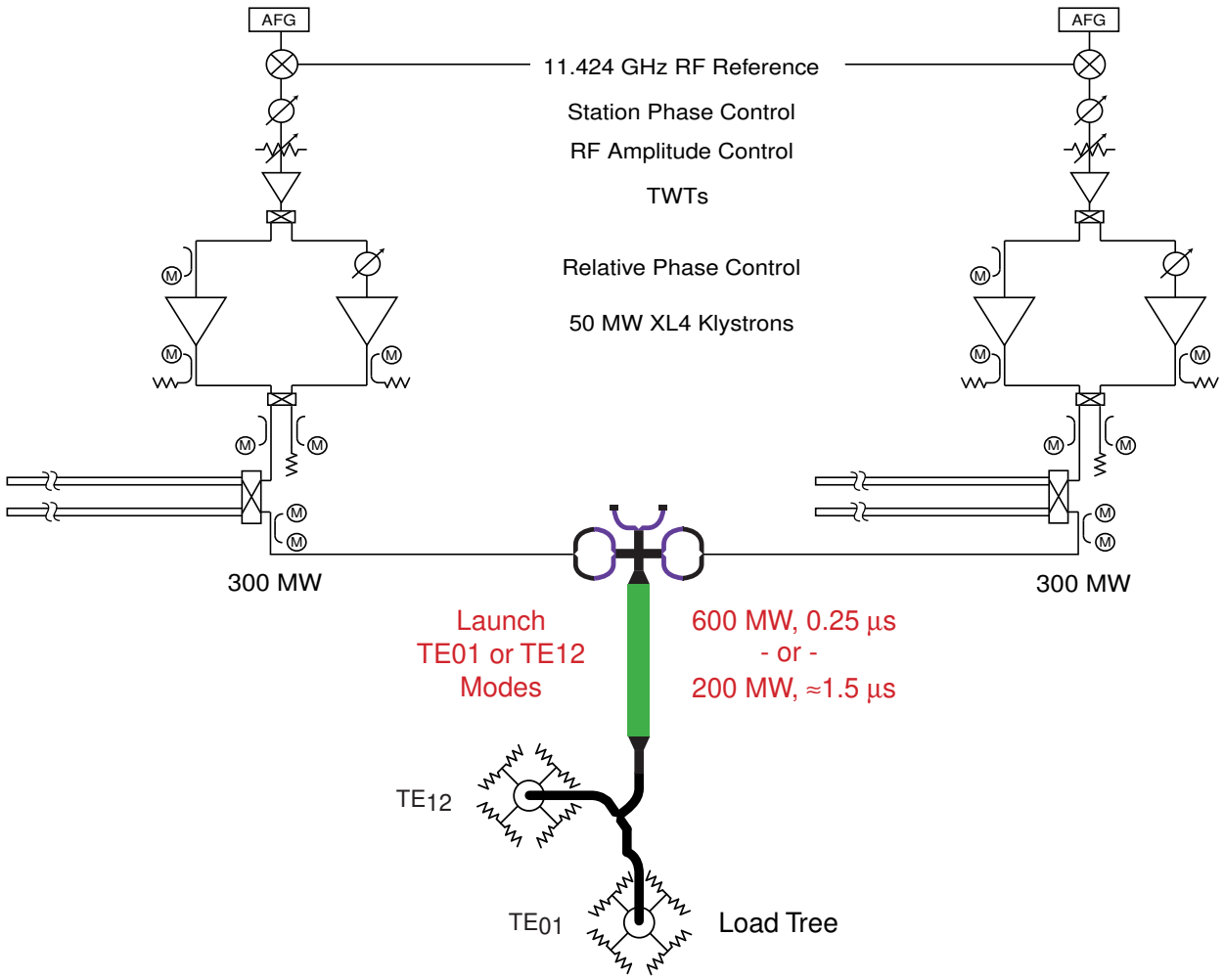


4 Delay Lines, 2 Modes/Line
Effective Compression Ratio=8
Klystron Pulse Width=3.05 μs → Accelerator Pulse Width=0.381 μs
Total Waveguide Length=174 km (for a 500 GeV Collider)

DLDS Pulse Compression Test

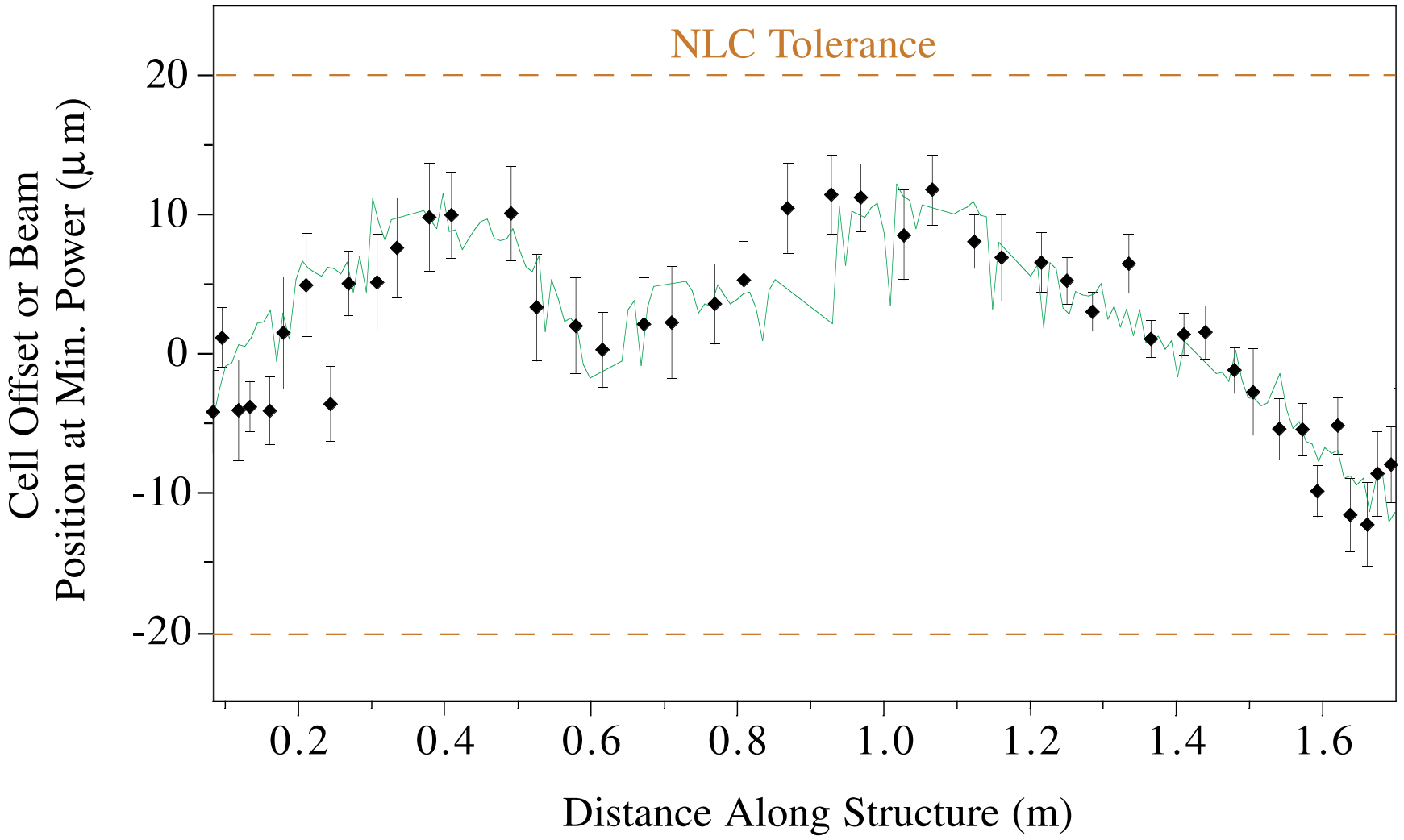
- All components have been designed
- Multi-mode transmission properties have been verified
- High power tests will start in 2001
- Full system test in 2003

NLCTA Setup



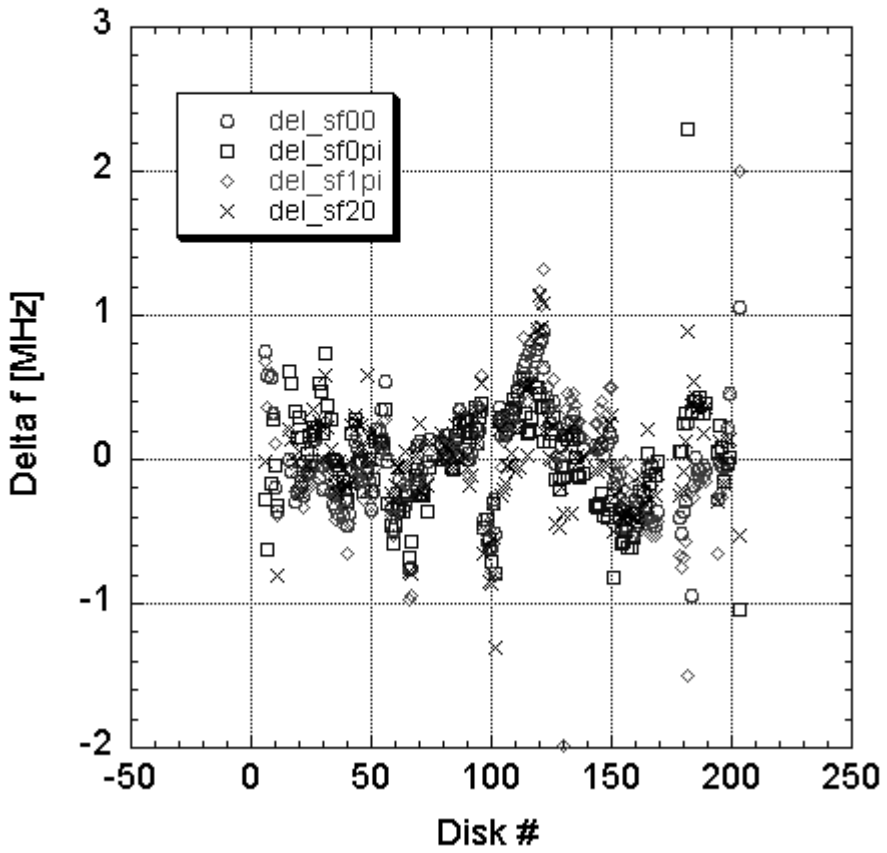
Accelerator Structures

DDS3 Structure BPM Test



RDDS1 Structure Construction

- RDDS1 cells were designed at SLAC and machined at KEK – final machining performed on diamond-turning lathe
- Attained excellent results: frequency errors less than 1 MHz, i.e. <1μm errors
- Tolerances for dipole mode frequencies are 5 times looser!
- Bonding process still needs to be understood!



High Power Damage

- Have had difficulty processing 1.8m long structures to 70 MV/m (NLC design gradient)
  - Single cells can operate at 150 ~ 200 MV/m without damage
  - A 26 cm structure has been run to 140 MV/m (some damage)
  - A 75 cm structure has been run at 90 MV/m (some damage)
  - Observed significant damage in 1.8 m structures at 50 MV/m
- Recent workshop on rf breakdown phenomena
- Theoretical model predicts the *damage* is related to the group velocity of the rf power in the structure
- Building 12 structures with KEK to study length and group velocity dependence – will be tested in 2001
- Studying cleaning and improved manufacturing techniques

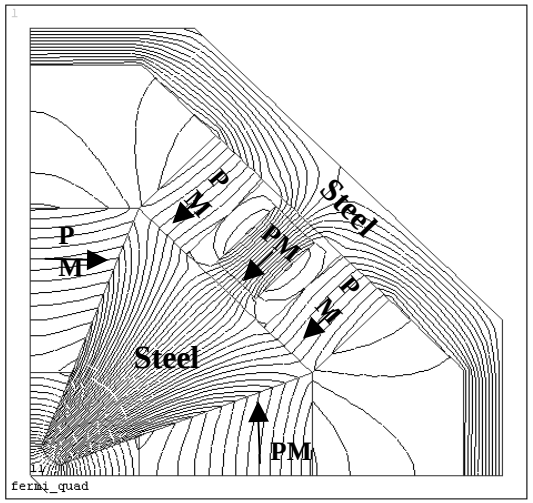
NLC RF System Highlights

- Developing solid-state modulator with LLNL
  - Much less expensive, more reliable, smaller package
- Demonstrated (periodic permanent magnet) PPM 75 MW klystron operation for NLC with 3μs rf pulse (2x expected!)
  - Half as many klystron/modulator systems required!
- Tested mode propagation needed for multi-moded DLDS
  - Less expensive rf pulse compression system
- Built DDS3 structure and RDDS1 structure with KEK
  - DDS3 exceeded alignment requirements and demonstrated rf BPM
  - RDDS will shorten linac length by 6%—sub-micron errors in cell fabrication
- Starting intensive gradient studies with CERN and KEK
- High power component tests finished in 2001 and full system test in 2003

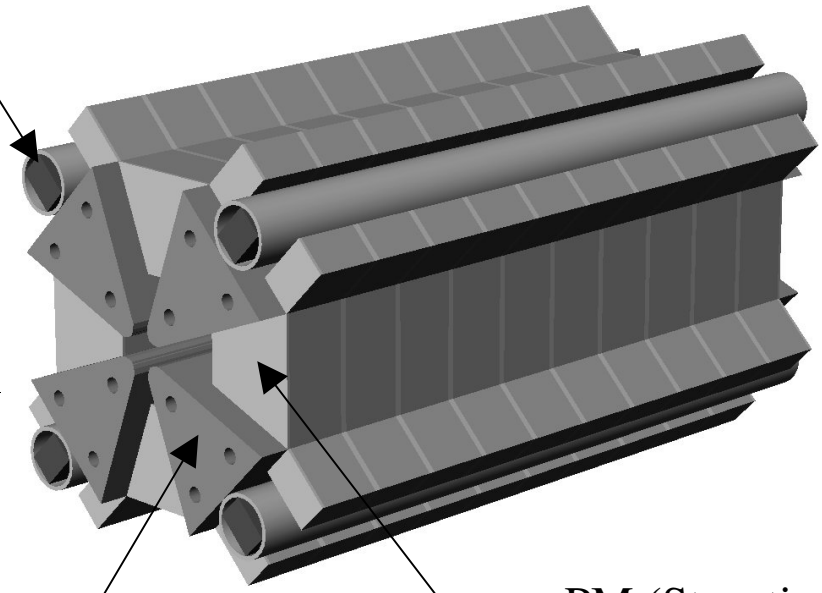
NLC Cost Reduction Strategy

- Costs distributed throughout system ⇒ attack all
- Primary changes:
  - Solid state modulator (powers 8 klystrons for 40% of the cost)
  - Longer linac rf pulses (half as many klystrons/modulators)
  - Permanent magnets (eliminate cable plant/PS, improved reliability)
  - Cut & cover tunnels (lower cost but may need terrain following)
  - Moving electronics to tunnel (eliminate cable plant)
  - Redesign bunch compressors (lower final energy, shorter system)
  - Redesign collimation system (reduce length of by factor of two)
  - New final focus (reduce length and components in BDS)
- Expect reduction in cost by 30% with another ~10% possible from scope reduction **if desired**
- Additional gains from further R&D and layout changes

FNAL Prototype PM Quad



Rotatable PM (Nd-Fe-B) Block to Adjust Field (+/– 10%)



PM (Strontium Ferrite) Section

Steel Pole Pieces (Flux Return Steel Not Shown)

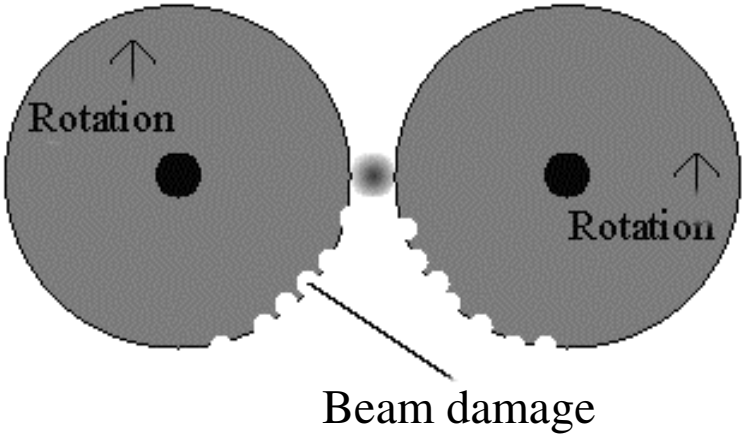
Mechanical Adjuster Concerns

- Calibration
- 1 μm Magnetic Axis Stability
- Response Time
- Reliability

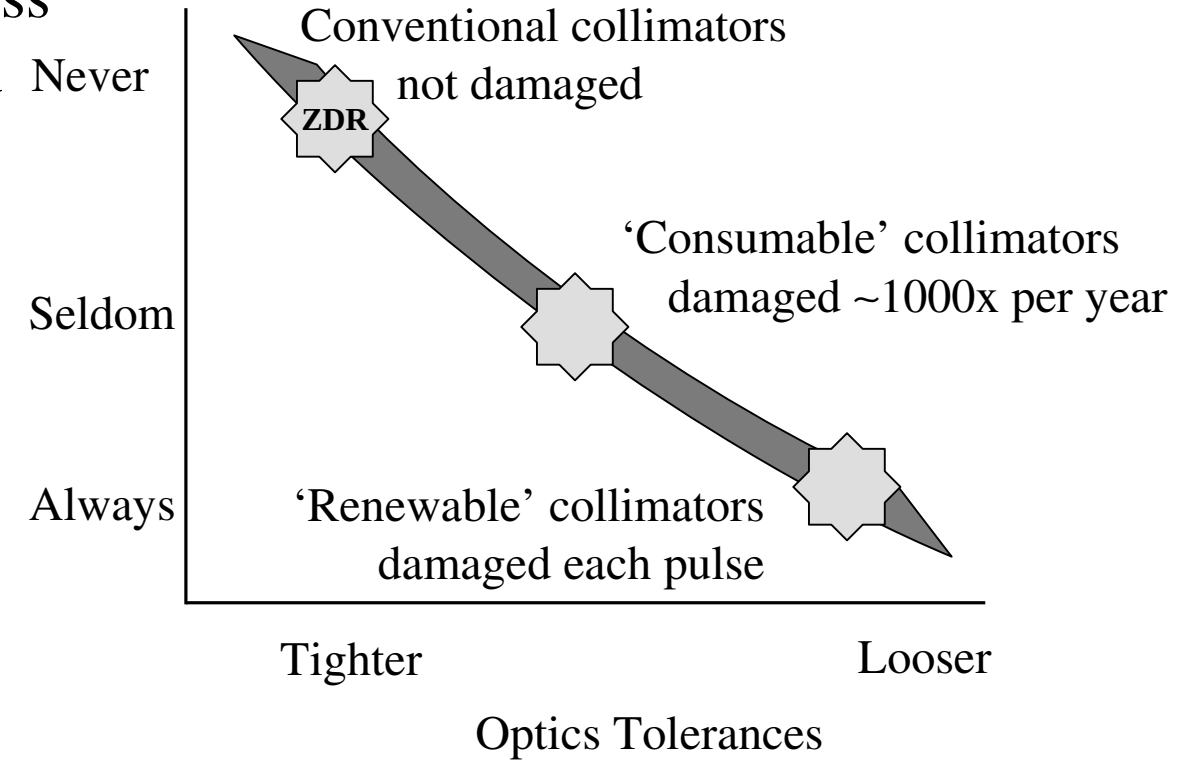
Post-Linac Collimation System

- High power beams will damage collimators unless beam sizes are increased
- Studying 'consumable' and 'renewable' collimator systems

Consumable Collimators



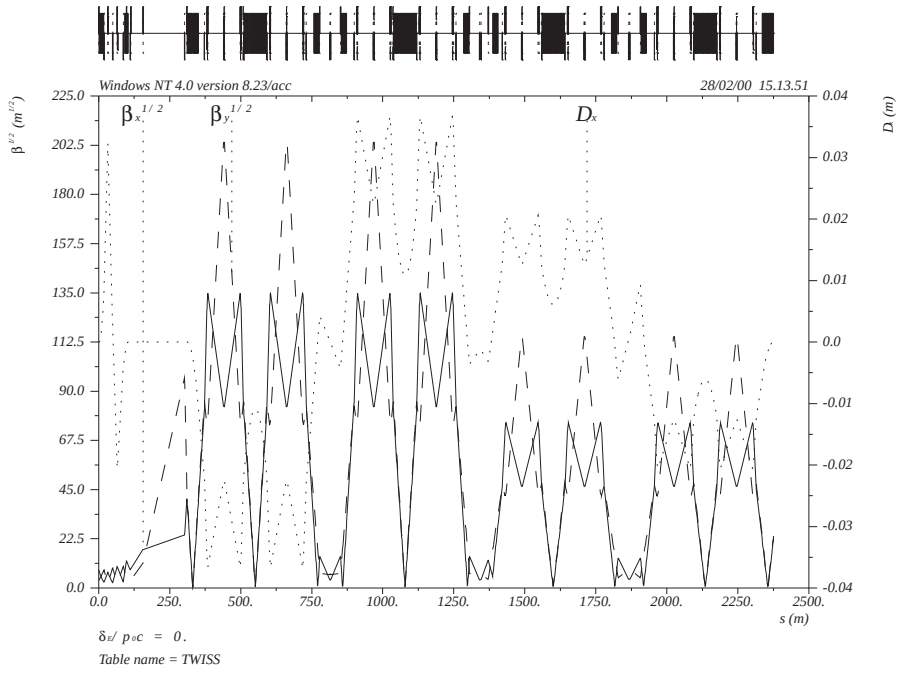
Single Pulse Collimator Damage

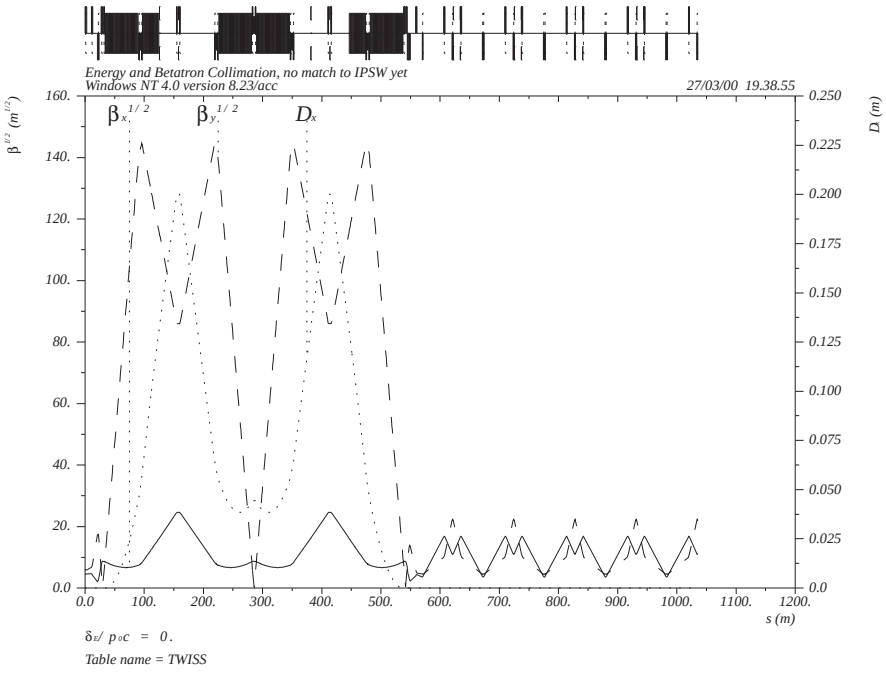


- Experimental study of collimator wakefields

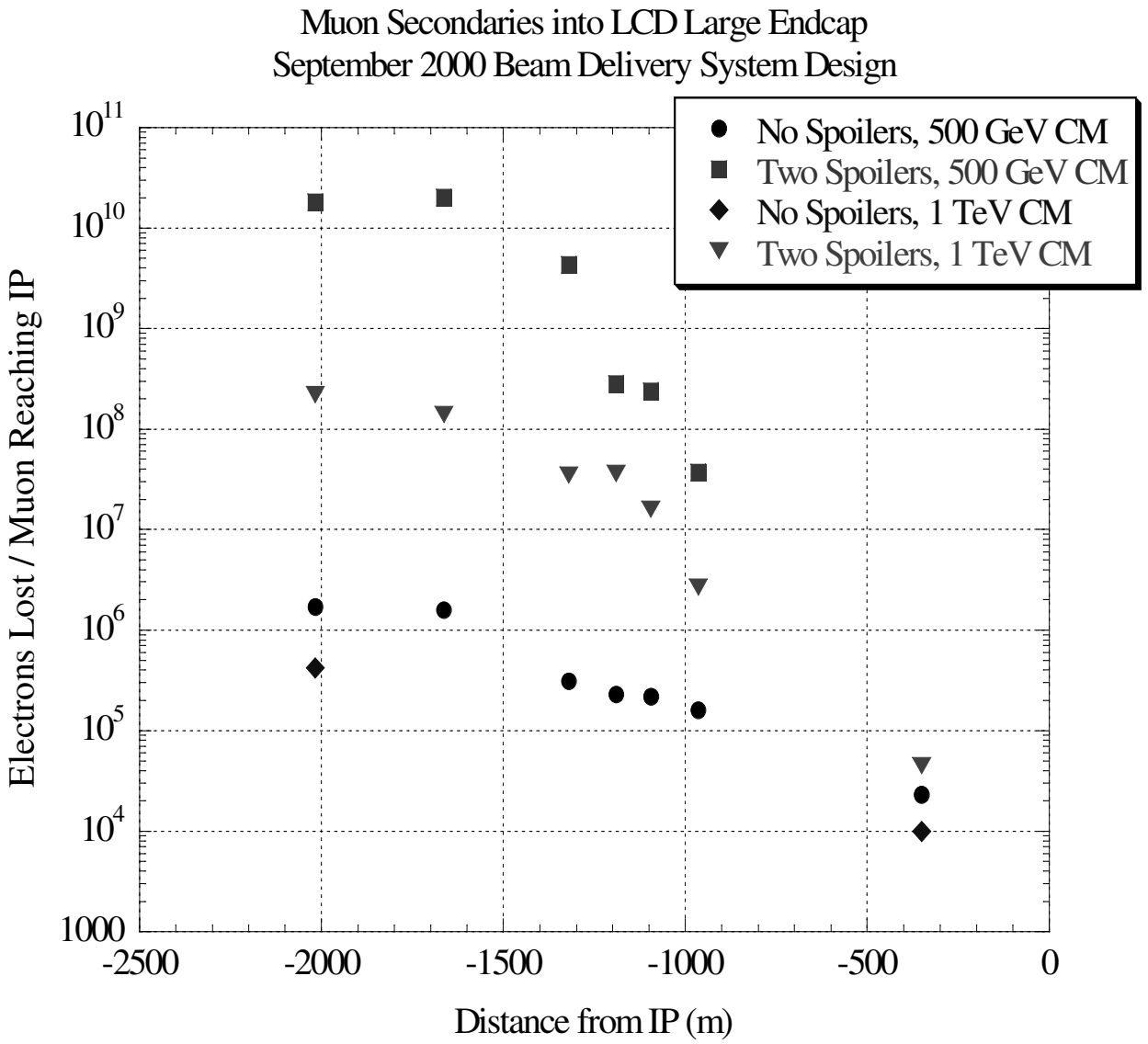
Post Linac Collimation

- Most main linac faults will be energy errors ⇒ design for passive energy collimation
- Infrequent betatron errors ⇒ ‘consumable’ betatron collimation
- Reduce collimator system length from 2.5 km to roughly 1.2 km—still working on optimal design





Collimator Muon Production



Final Focus and Interaction Region

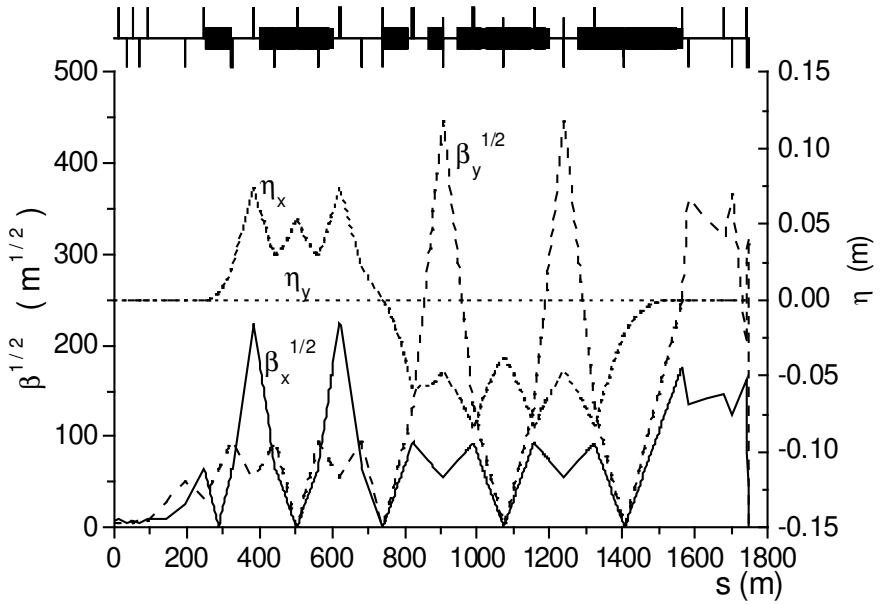
- Old final focus was a scaled up model of the SLAC Final Focus Test Beam (FFTB) beamline
- Modular design with orthogonal control using symmetry
- Chromatic correction is performed with pairs of sextupoles at large dispersion points separated by π to cancel geometric aberrations—requires lots of bending to generate η
- Length of system: was roughly 1.8 km—driven by synchrotron radiation at 1.5 TeV
- New design: chromatic correction is performed at final doublet so synchrotron radiation has little effect

$\Rightarrow$ Length is roughly 700m and will operate at 5 TeV!

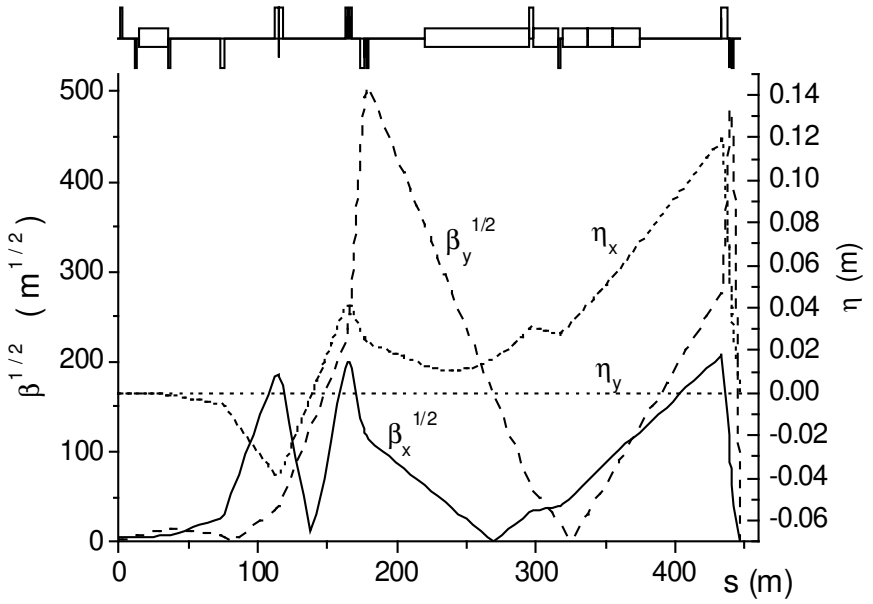
New Final Focus

- One third the length - many fewer components!
- Can operate with 2.5 TeV beams (for 3 ~ 5 TeV cms)
- 4.3 meter L* (twice 1999 design without tighter tolerances)
- Optical functions are not separated and dispersion in the FD

1999 Design



2000 Design

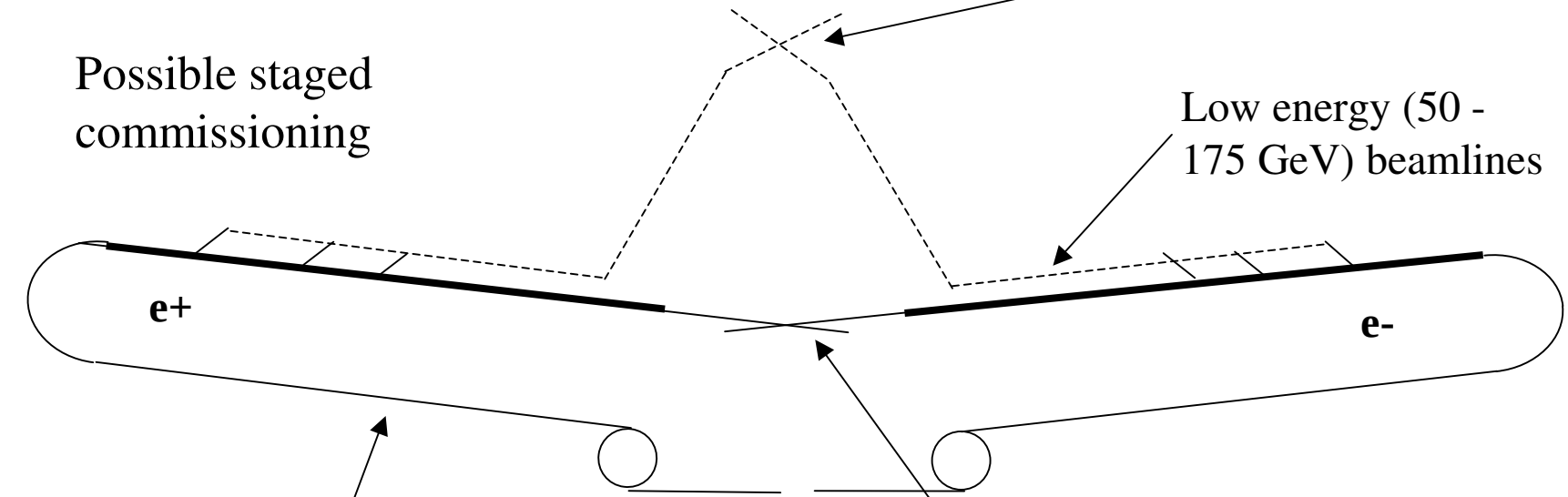


Hi/Lo IR Layout

- Final focus aperture is set by low energy beams $\sigma \sim 1/\sqrt{\gamma}$ but highest energy operation is limited by magnet strength, synchrotron radiation and system length
  - $\Rightarrow$ Final focus has limited energy range without rebuilding magnets and vacuum system
- Simplify design by dedicating one IR to 'low' energy operation and one to 'high' energy operation
  - 'Low' energy range of 90–350? GeV (build arcs for 500 GeV)
  - 'High' energy range of 250–1000 GeV (with upgrade to 1.5 TeV)
- High energy beamline would have *minimal bending* to allow for upgrades to very high collision energies
  - 'High' energy BDS could be upgraded to multi-TeV operation!

Hi/Lo IR Layout

Site roughly 26 km in length with two 10 km linacs



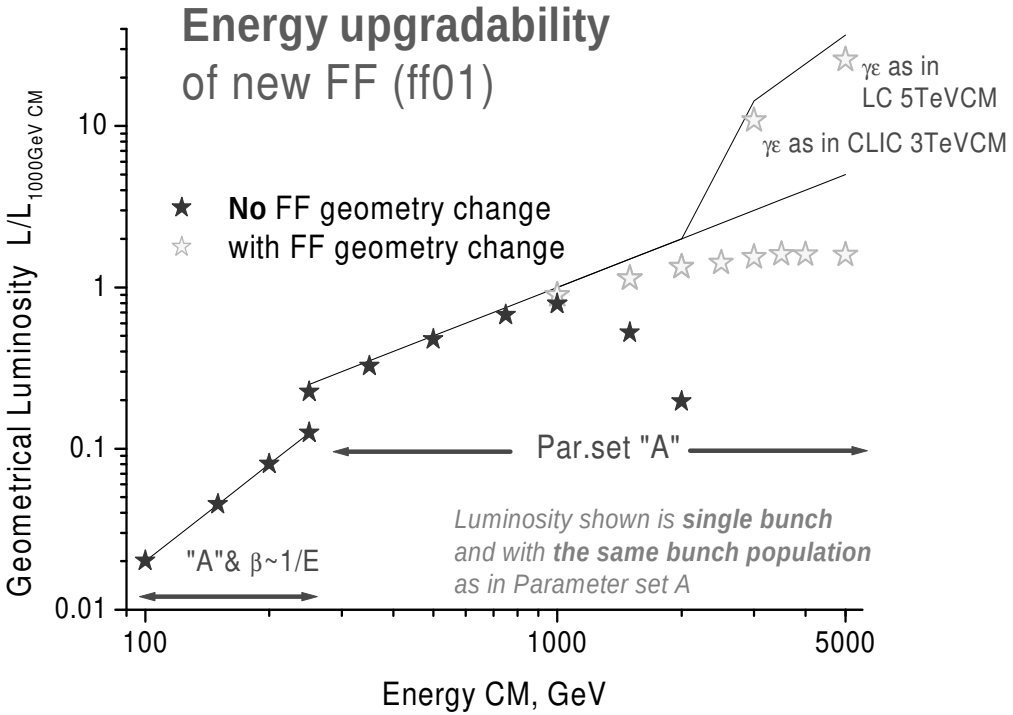
Luminosity Scaling with Energy

- Assuming same injector, the luminosity scales as:

  Low Energy : $L \propto \gamma^2$ (aperture limited)

  Mid Energy : $L \propto \gamma$ (bunch length limited)

  High Energy : $L \propto \gamma^{-2.5}$ (SR limited)



- Luminosity in high energy FF scales linearly with energy between 250 and 1 TeV
- Low energy FF scales similarly but at lower energy!

Design versus Intrinsic Luminosity

- Intrinsic luminosity:
  - this is the luminosity the machine could deliver limited by physical effects
- Design luminosity:
  - this includes operational limitations and is the luminosity for which the collider is *designed*
  - includes use of tuning techniques developed during SLC operation

Example: $\Delta\varepsilon$ at 500 GeV cms
$\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ [10-8 m-rad]

	Intrinsic	**Design**
Damping rings	300 / 2	300 / 2
Main Linac	315 / 2	330 / 3
Beam delivery	330 / 2	360 / 3.5
Lum.	30×10^{33}	22×10^{33}

Luminosity Evolution

- Previously NLC was aimed at *L* goal of 1×10^{34} at 1 TeV
- NLC was based on large 'operating plane' with 50% spot size and charge variation **plus** built-in margins including 50% charge overhead and 300% $\Delta\varepsilon$
- Components were spec. to tightest tolerances over range
  - NLC damping rings spec. to produce $\gamma\varepsilon_y = 0.02$ mm-mrad although only 0.03 mm-mrad is required initially
  - SLC used 'emittance bumps' to reduce emittance dilution from 1000% to 100%—technique not included in initial emittance budget
  - NLC is a 2nd generation LC - many tools and techniques were developed for SLC and used at FFTB and more recently PEP-II
- Design luminosity is 4x higher than 'operating plane' values
- Actually, present prototypes and R&D results are even better!
  - $\Delta\varepsilon_y < 25\%$ in linac if production components are similar to prototypes

Design Parameters

High E IP Parameters (2/00)		
	Stage 1	**Stage 2**
CMS Energy (GeV)	490	888
Luminosity (10^{33})	**22**	**34**
Repetition Rate (Hz)	120	120
Bunch Charge (10^{10})	**0.75**	**0.75**
Bunches/RF Pulse	190	190
Bunch Separation (ns)	1.4	1.4
Eff. Gradient (MV/m)	**50.2**	**50.2**
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 2	300 / 2
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	360	360
$\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	**3.5**	**3.5**
β_x / β_y at IP (mm)	8 / 0.10	10 / 0.12
σ_x / σ_y at IP (nm)	**245 / 2.7**	**200 / 2.2**
σ_z at IP (um)	110	110
Υave	0.11	0.26
Pinch Enhancement	1.43	1.49
Beamstrahlung δB (%)	4.6	8.8
Photons per e+/e-	1.17	1.33
Two Linac Length (km)	5.4	9.9

Low Energy IP Parameters (8/00)			
CMS Energy (GeV)	**92**	**250**	**350**
Luminosity (10^{33})	**3.5**	**9.4**	**13.2**
Repetition Rate (Hz)	**120**	**120**	**120**
Bunch Charge (10^{10})	**0.75**	**0.75**	**0.75**
σ_x / σ_y at IP (nm)	**630 / 6.2**	**380 / 3.8**	**320 / 3.2**
L0 / Ltotal (%)	62	47	43
Beamstrahlung δB (%)	0.18	1.1	2
Photons per e+/e-	0.49	0.79	0.92
Polarization loss (%)	0.08	0.21	0.34

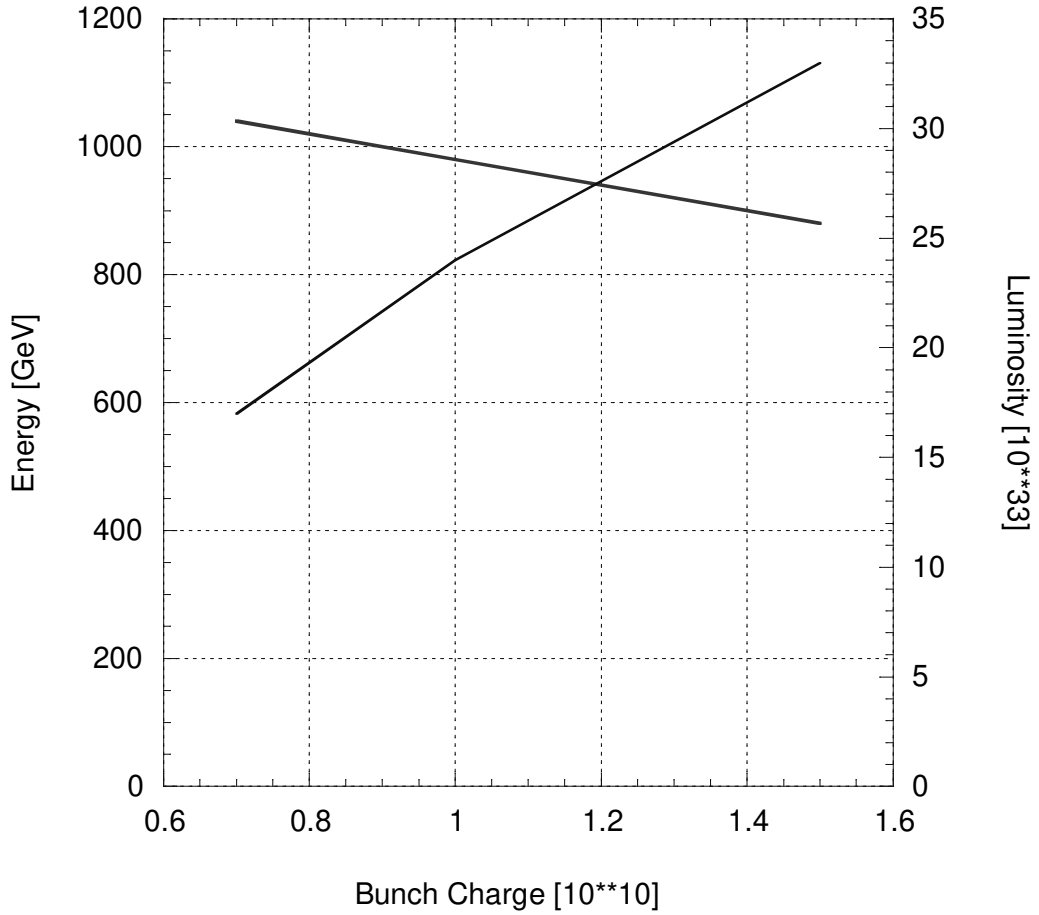
- Trade luminosity versus beamstrahlung:

$$L \propto \frac{N^2}{\sigma_x \sigma_y} \qquad \delta_B \propto \frac{N^2}{\sigma_z \sigma_x^2} \qquad \delta_E \propto \frac{N}{\sqrt{\sigma_z}}$$

increase $\sigma_x \rightarrow \delta_B$ decreases faster than L

Beam Loading

- CMS energy changes with beam current due to beam loading
- Luminosity also scales with beam current



180 Hz Operation Possibility

- 180 Hz operation is decoupled from low/high energy IR
  - two options: 180 Hz at 500 GeV or 120-60 Hz at 500 GeV and 60-120 Hz at lower (250 GeV) energy
  - Choice depends on AC power
- Primary issues are:
  - power consumption, average heating and radiation
  - machine protection (60 Hz minimum operation for any low ε beam)
  - emittance generation / damping rings must be redesigned
  - duplicate BDS beam lines for dual energy operation
- Might start low energy IR before before completion of high energy IR and full facility

Outstanding Issues (a few of many!)

- Sources
  - Current limit in e- source and target limits in e+ source
- Damping rings
  - Require excellent stability
  - In addition to conventional instabilities, new effects may be important
- RF breakdown
  - Difficulty processing up to 70 MV/m and damage at 50~60 MV/m
  - 450 Joules in DLDS rf pulse compression system
- Collimation and IR
  - Have to collimate 'all' particles outside $8\sigma_x$ and 40 σ_y without destroying collimators or beam emittance
  - Need high field magnets in IR with nm-level stability
- Reliability

Summary

- Lots of progress on NLC design in last year!
- Lehman review positive but cost was too high!!

- Continual improvement in rf components ⇒ cost reductions
- More aggressive approach to design ⇒ cost reductions
- New concepts ⇒ cost reductions
- Lots of ideas for further improvements

- Expect ~30% cost reduction with further reduction possible from additional R&D and/or scope reduction

- NLC is designed for high luminosity (similar to TESLA) ***however*** neither design has much margin at these parameters
- NLC facility will be designed to support a future multi-TeV LC