Linear Collider: Accelerator Overview

April 2003 APS Meeting

06-Apr-2003

Overview of the Overview

- Linear vs Circular Collider @ 1 TeV CM
- The Generic Linear Collider (GLC)
- The Stanford Linear Collider (SLC)
- Luminosity Challenges
- Energy Challenges
- Integrated Simulations
- Conclusions

Linear vs Circular

- Historically: circular colliders were the machine of choice in HEP – "easier"
- But not at ultra-high energy for electrons! SR scaling:

$$U_0\ [\text{GeV/turn}] = 8.85 \times 10^{-5}\ E^4[\text{GeV}]\ /\ r[\text{m}]$$

- Ring RF system must replace this loss
- Balance length costs vs RF system costs
  - r scales approximately as E^2
  - LEP @ 100 GeV/beam: 27 km around, 2 GeV/turn lost
  - Scale to 500 GeV/beam:
    - 675 km around
    - 51 GeV/turn lost!

Linear vs Circular (2)

- Consider also the luminosity
  - For desired luminosity (~10^{34}/cm^2/second), existing rings use ~amperes of beam current
  - 50 GeV/turn x 2 amperes = 100 GW RF power!
  - For scale: the state of California consumes ~45 GW in the summer
- Both the size and the power needs of a circular collider @ 1 TeV CM, L = 10^{34}/cm^2/second, seem excessive

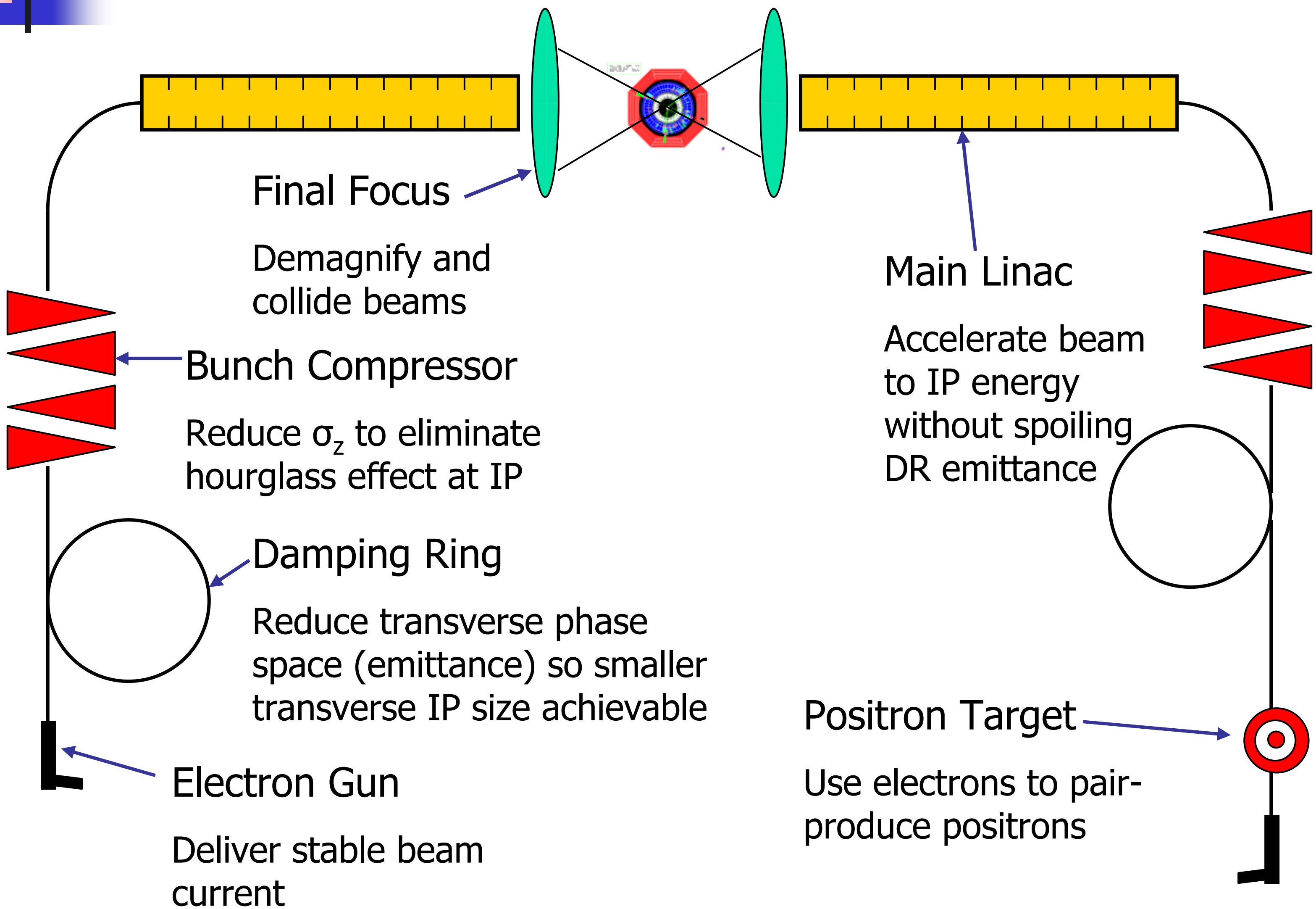
The Generic Linear Collider (LC)

- The linear collider design is largely shaped by luminosity (and economic) requirements:

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

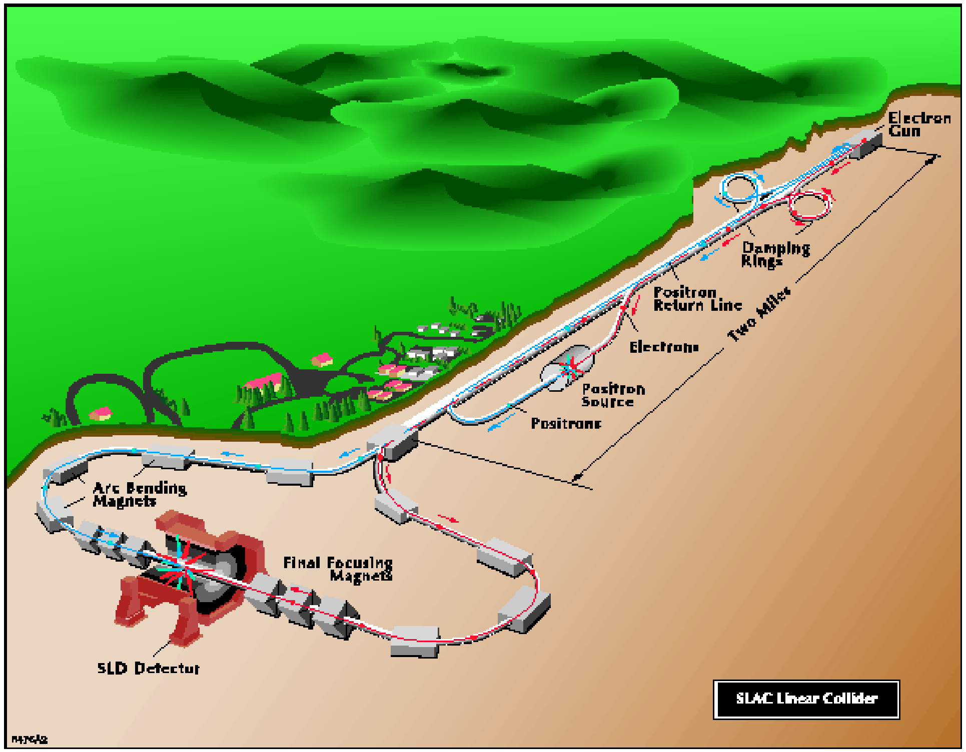
- H_D (Enhancement from beam-beam focusing) is typically 1.5 ± 0.5
- E_{cms} set by experimenters (0.5-1.0 TeV)
- N/σ_x limited by beam-beam backgrounds
  - 10^{10} particles and 400 nm "typical" values (round #'s)
- Beam power and IP vertical spot size parameters available to designers
  - 5 MW and 4 nm "typical" values (round #'s)

LC(2)



Final Focus
Demagnify and collide beams
Main Linac
Accelerate beam to IP energy without spoiling DR emittance
Bunch Compressor
Reduce σ_z to eliminate hourglass effect at IP
Damping Ring
Reduce transverse phase space (emittance) so smaller transverse IP size achievable
Positron Target
Use electrons to pair-produce positrons
Electron Gun
Deliver stable beam current

The Stanford Linear Collider (SLC)



Used the SLAC linac to co-accelerate e^+, e^- to 47 GeV

Bent beams around long arcs to collide @ Z-resonance

Had the full complement of pieces of a linear collider

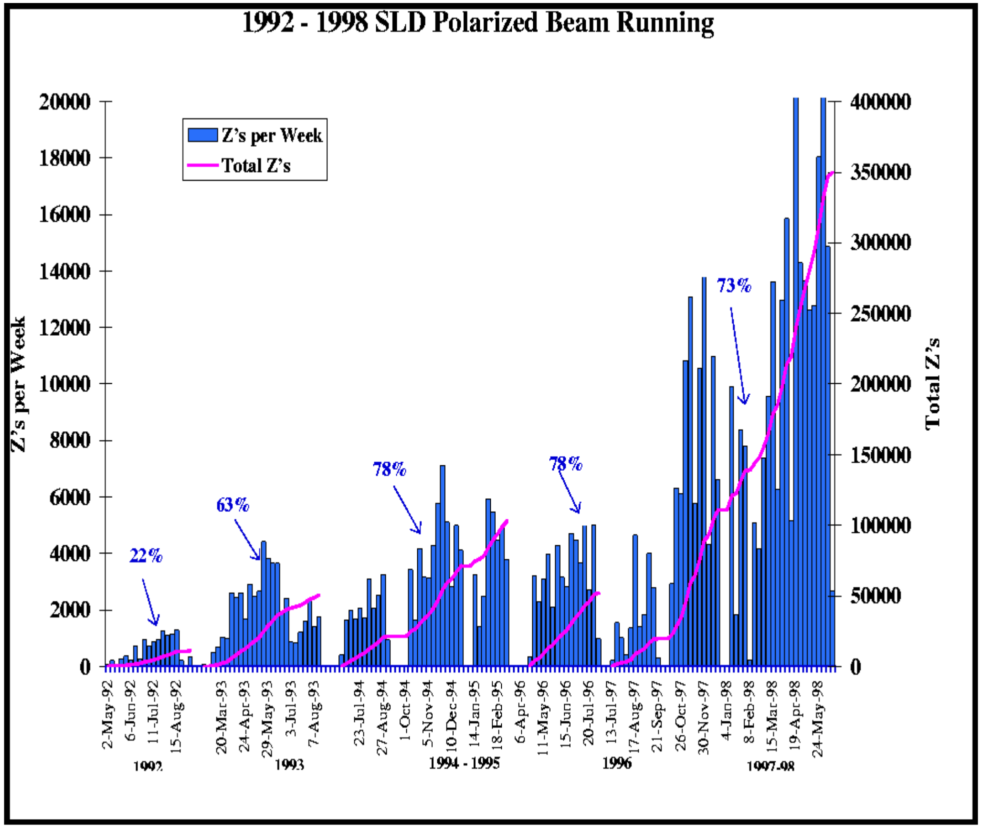
- electron source
- positron target
- damping rings
- bunch compressors
- main linac
- Final Focus

SLC(2)

SLC was immediately recognized as the most difficult collider ever built, a title it still holds

Many problems were “implementation-specific” (related to fitting SLC on existing SLAC site)

Others related to the unprecedented stability, precision diagnostics, controls, management of beam dynamics needed to reliably deliver ultra-small beams at the IP (2 μm x 0.7 μm RMS ultimately achieved)

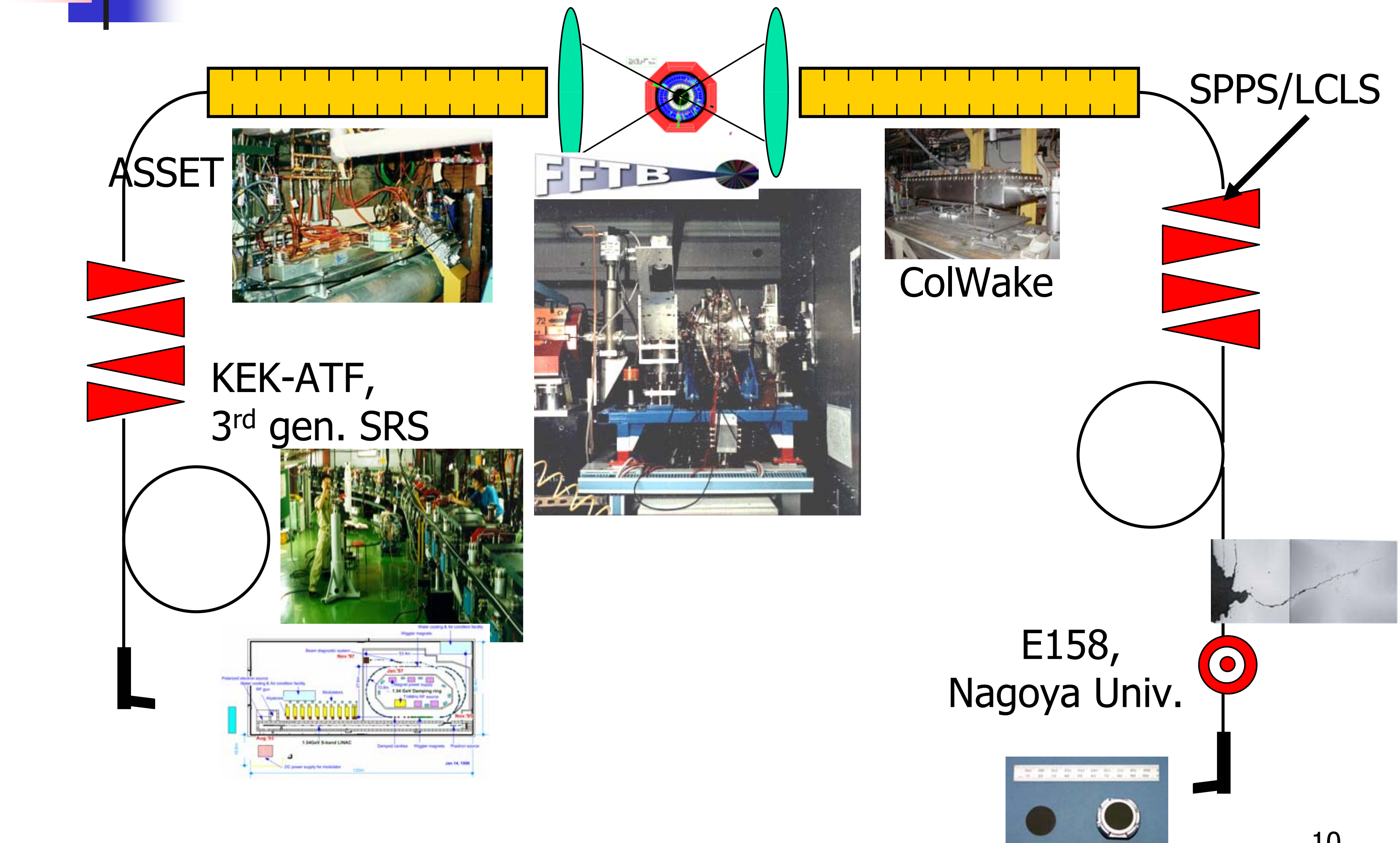


The SLC ultimately delivered L = 2×10^{30}, 5×10^{5} Z^0’s produced with polarized electrons, and a real understanding of the challenges of a linear collider

Luminosity Challenges

- All related to the difficulties of generating small *emittances* and strong *IP Focusing* with a large *beam current*
  - Damping ring: low emittance, flat beams, short damping time, fast injection/extraction, collective instabilities
  - Bunch Compressor: Incoherent and Coherent Synchrotron Radiation
  - Main Linac: Dispersion, wakefields
  - Final Focus: chromatic and geometric aberrations, xy coupling, synchrotron radiation, IR backgrounds, collimator wakefields, colliding small spots
  - Everywhere: adequate diagnostics and controls

Luminosity Challenge (2)



Energy Challenge

- SLAC linac is longest, highest-energy linac on earth
  - 2856 MHz frequency
  - 3 m structures x 1000
  - 50 GeV acceleration
- Why not just build a "Super-SLAC"?
  - Low gradient – 1 TeV CM = 60 km of linac
  - Low efficiency – 1 TeV CM = 600 MW RF power
  - Low Luminosity – strong wakefields, other problems
- 1960's SLAC linac technology is poorly-matched to LC challenge

Energy Challenge (2)

If 1960's SLAC technology won't do it, what are the alternatives?

Lower Frequency (1.3 GHz) → Superconducting (2 K, Nb) → TESLA (TeV Electron Superconducting Linear Accelerator)

Higher Frequency (11.424 GHz) → Room Temperature, Cu → JLC/NLC (Japan/Next Linear Collider)

Superconducting Linac for LC

Advantages

- Low frequency – wakes weak, klystrons easy
- Low power loss in walls of structure
- Low input power (230 kW per structure)
- Low beam current (8 mA)
- Long bunch spacing (337 nsec) so bunch-by-bunch control easy
- Standing-wave cavities have gradient uniform along length

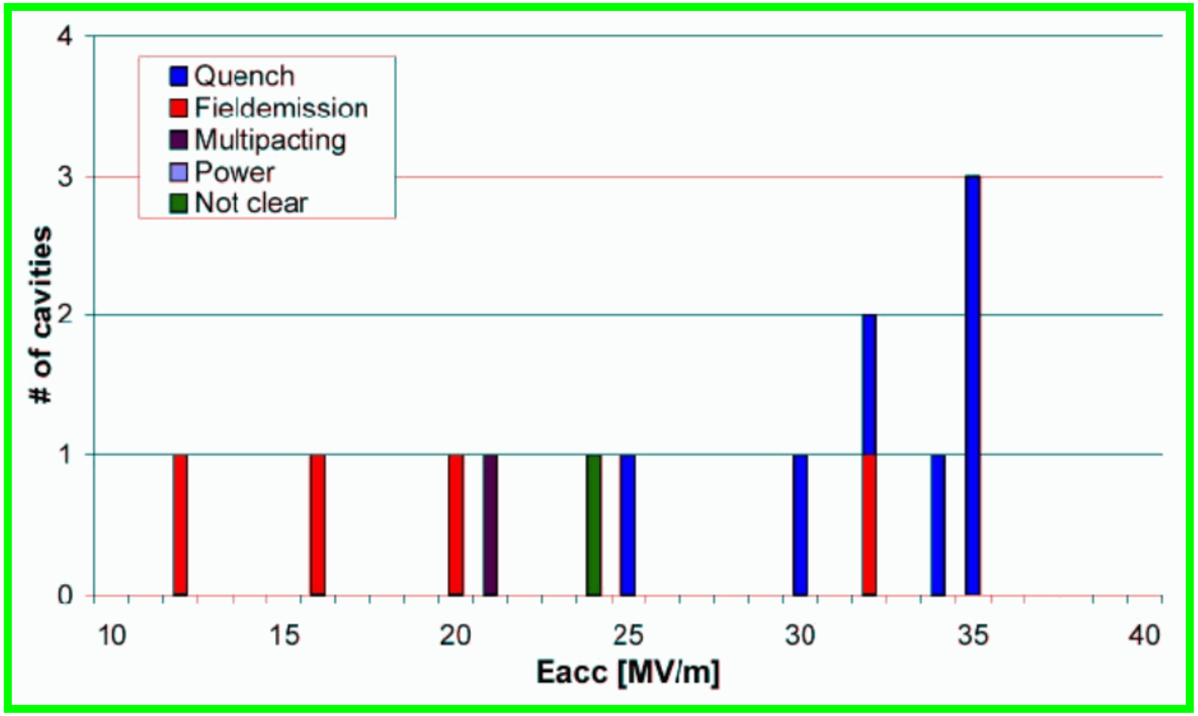
Disadvantages

- Tight frequency tolerances, mechanical tuners needed on all cavities
- Beam instrumentation more difficult (large apertures)
- Long bunch train (~3000 bunches/pulse) requires long DR (17 km around)
- Low repetition rate (5 Hz) makes train-by-train control hard
- Low gradients (more on this momentarily)
- Complicated cryogenic system in tunnel

Gradient of SC Cavities

TESLA Test Facility (TTF) at DESY

High gradient hasn't historically been a huge priority for SC linacs; LC demands it!



DESY R & D program has achieved 35 MV/m in 9-cell cavities

1 TeV CM LC would require < 30 km linac structures

High-Frequency Linac for LC

Advantages

- High frequency more efficient
- Higher gradients available
- Frequency tolerance looser than SC
- High repetition rate good for train-by-train control
- Short trains good for damping ring
- Beam instrumentation easier

Disadvantages

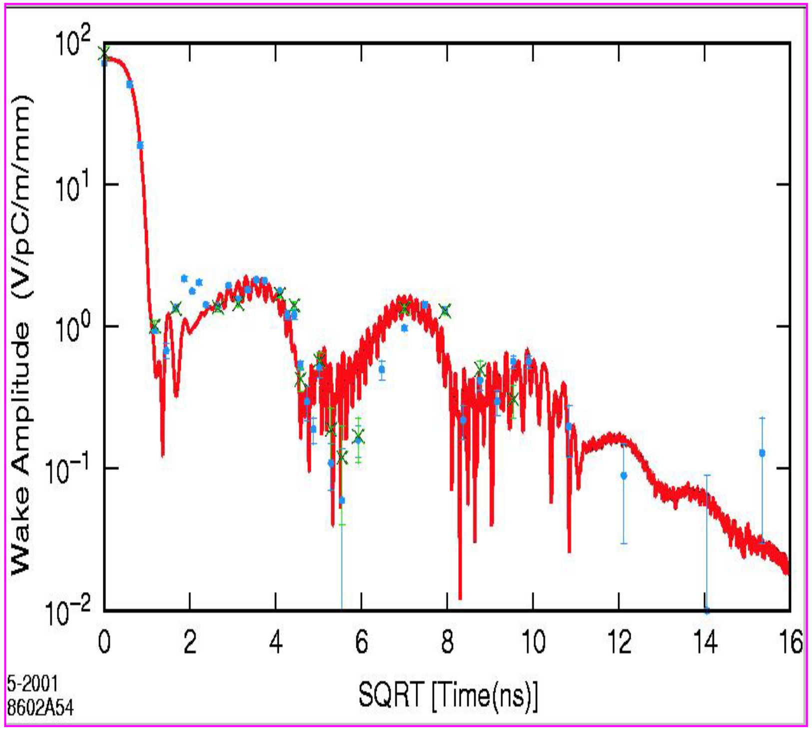
- Strong wakefields – beam based alignment required
- High power (100 MW per structure) required
- Klystrons harder
- Short bunch spacing (1.4 nsec) hard for bunch-by-bunch control
- Wall losses reduce efficiency
- Gradient in front of structure > average gradient

High-Frequency R & D

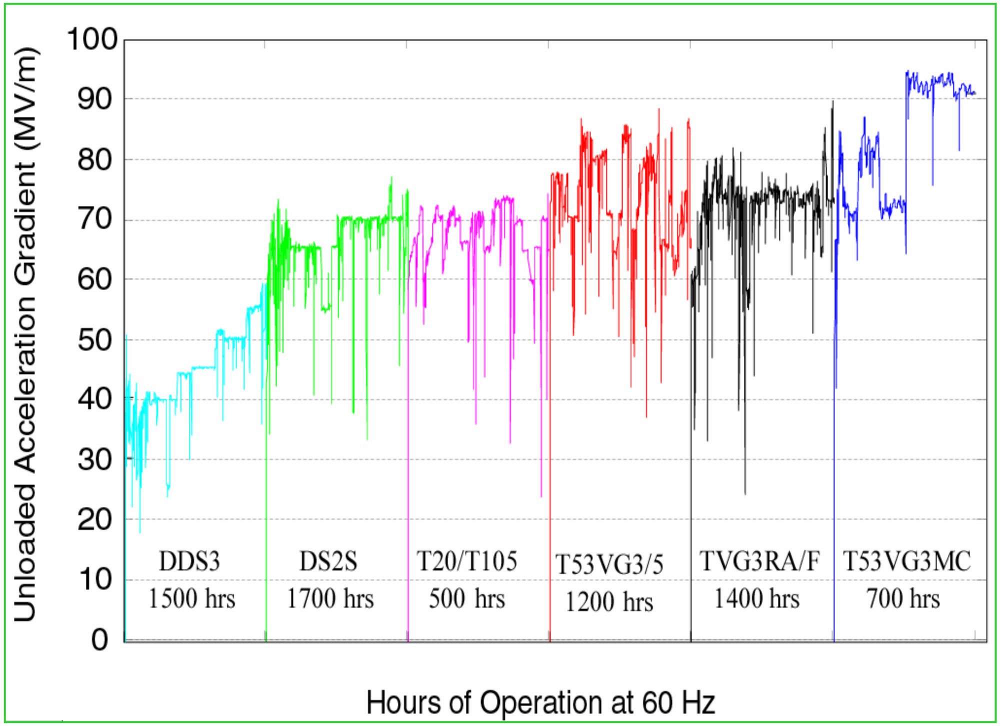
NLC Test Accelerator
(NLCTA) @ SLAC

Two main emphases: control of multi-bunch wakes and achieving high gradient

Wakes: Excellent reduction of MB effects (*will not be an issue*)



Gradient: 65 MV/m achieved with test structure, but not yet in "NLC-ready" structure

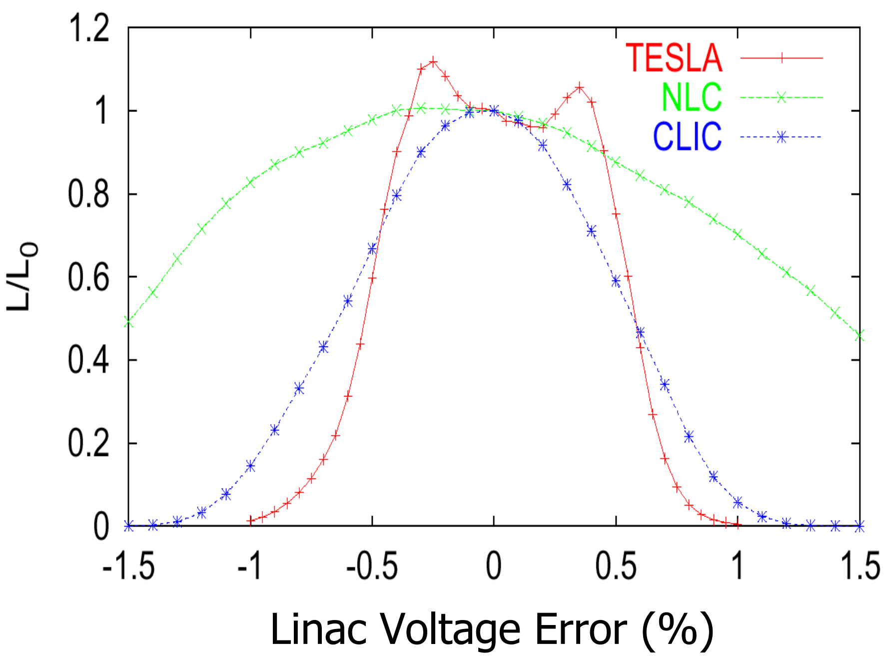


Integrated Simulations

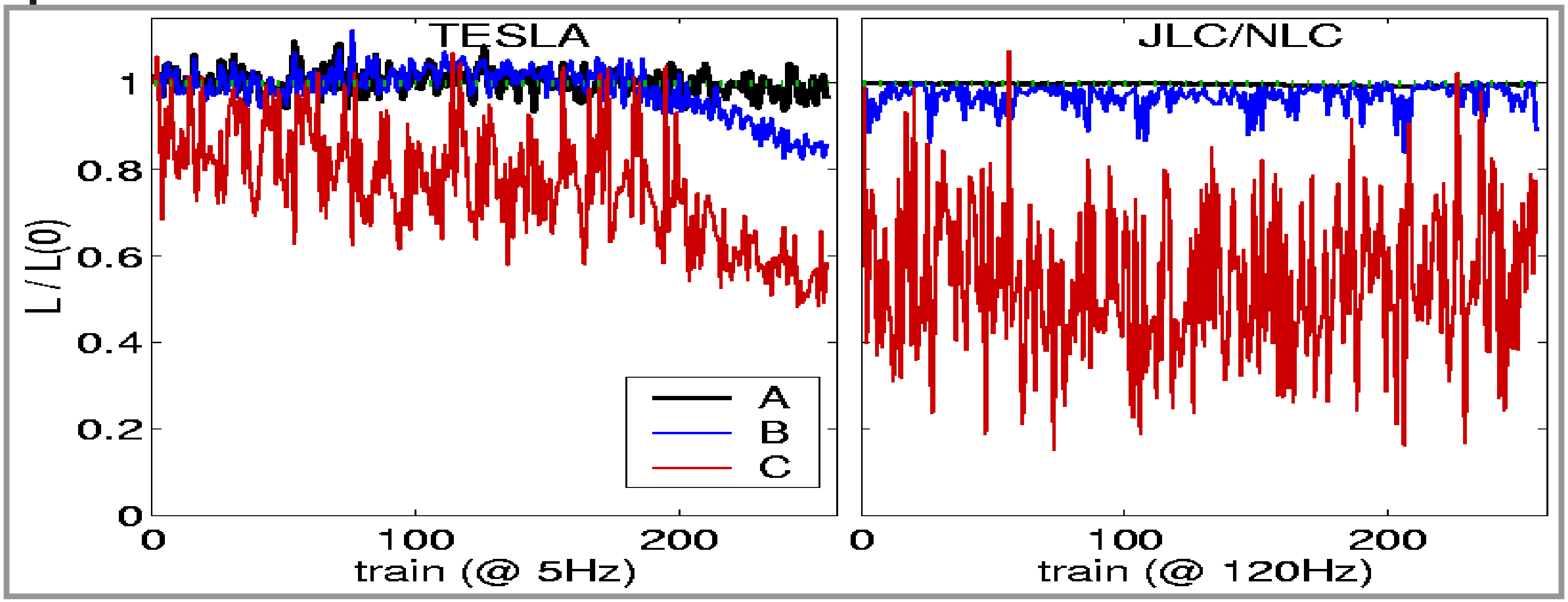
- All LC designs need copious beam-based tuning to achieve their design luminosities
- Interactions between tuning strategies in different parts of the machine are increasingly important
- Study of these issues hobbled by different simulation requirements of different parts of the machine
  - main linac: quads and RF structures
  - final focus: lots of high-order aberrations, beam-beam
  - bunch compressor: nonlinear compaction terms, etc
- New development in the last 2 years: codes that can really model tuning & operation from DR exit to IP

IntSims (1): FF Bandwidth

- Luminosity dependence on beam energy
- Historically, no satisfactory metric
- IntSim approach:
  - track beams thru linac & FF with linac voltage error
  - collide with beam tracked thru perfect linac & FF
  - Measure luminosity
  - Accurately simulates effect of linac voltage error
  - Includes fact that not all designs have same energy spread (E spread is a factor in bandwidth)



IntSims (2): Ground Motion



- 3 models of ground motion (inc. wavelike, diffusive, fast, slow, correlated, uncorrelated…) based on measurements around the world
  - "A" = quietest, "C" = noisiest
- Simulated full LC (2 sets of compressors, linacs, FF's, lumi from beam-beam interaction, collision feedbacks)

Conclusions

- A 0.5-1.0 TeV CM linear collider is a much more feasible route for e^+e^- than an equivalent storage ring
- The LC will be “the toughest collider you’ll ever love”
  - Valuable experience from SLC and numerous test facilities
  - Unprecedented simulation studies of tuning and operation have been performed and are ongoing
- Two prospective RF technologies are available
  - different (complementary?) strengths and weaknesses
  - Hopefully by the end of 2003 we’ll have a reliable idea of their capabilities