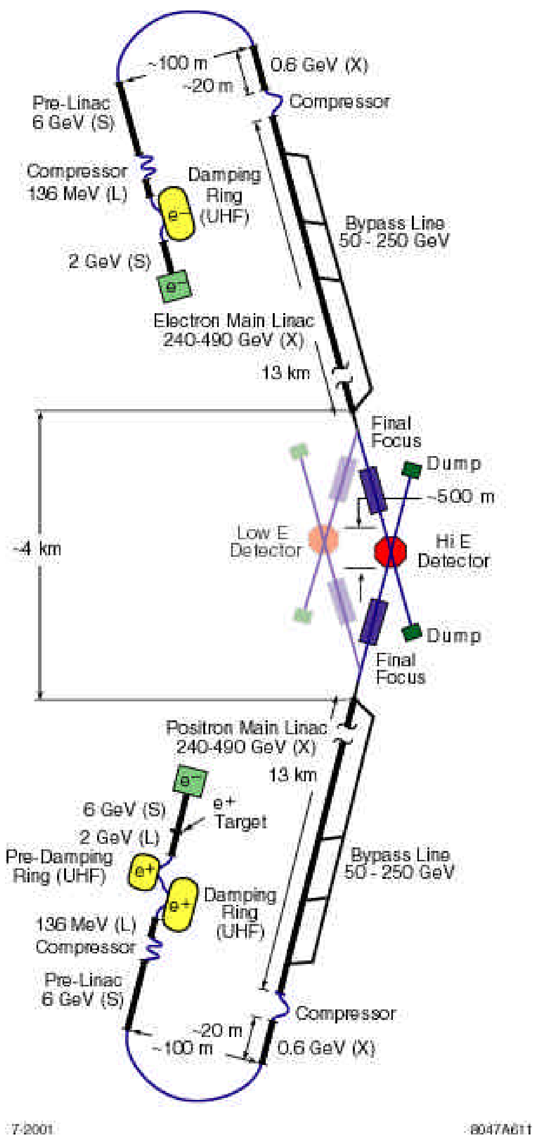


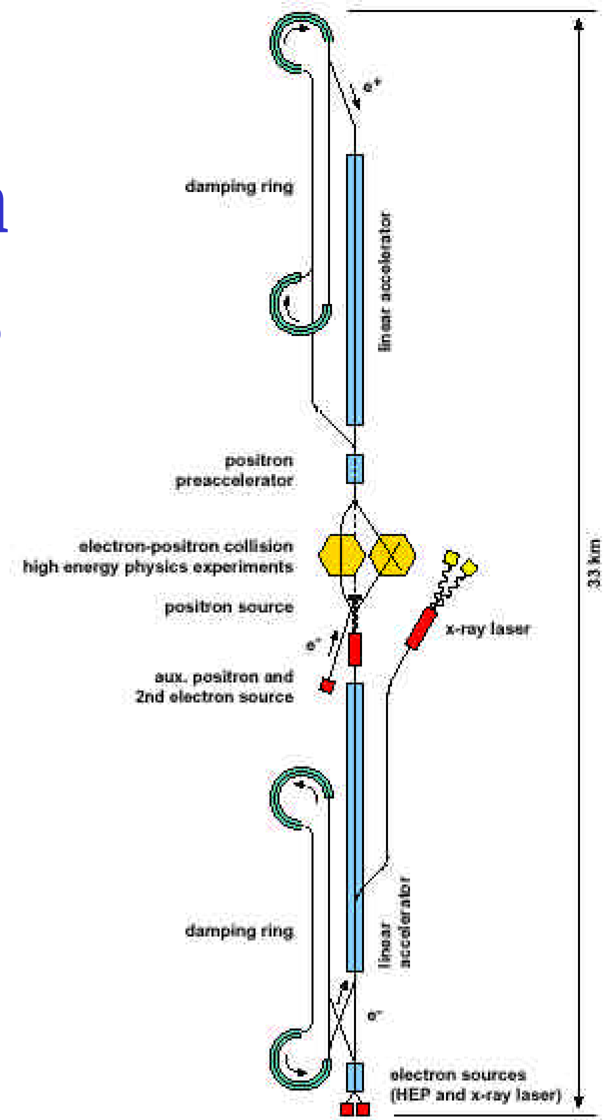
Next-Generation Linear Colliders

Tor Raubenheimer

SLAC

YPP Meeting

March 12th, 2003



Introduction

- The three regional advisory committees, ECFA, ACFA, and HEPAP, have recommended the LC as the next major HEP facility
  - All agree that this must be an international facility
  - Cost appears to by 5 to 7 B$ using US accounting practices
- The international HEP community has begun thinking about how to implement the LC
  - Lots of committees formed but real progress despite this!
- Interest from government science agencies
  - Partly for the science
  - Partly for the size
  - Partly for the international collaboration

Basic Requirements

Stage 1: Initial operation

500 GeV cms

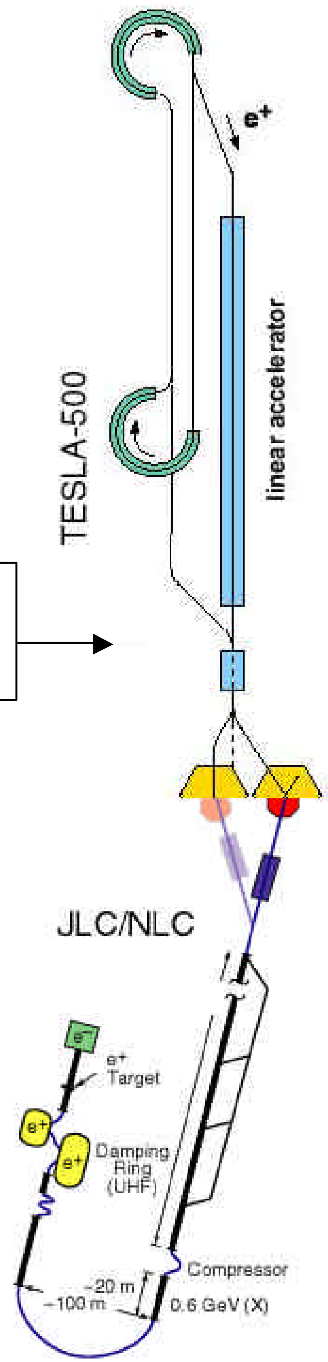
L = few x10^{34}

Stage 2: Needed capability

800 GeV ~ 1 TeV cms

L = few x10^{34}

PS. this does not really work!



Higher Energy Upgrades:

- 1.5 TeV with upgrade of linac rf system or length increase
- 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

Linear Collider Designs

- TEV Superconducting Linear Accelerator (TESLA)
  - Based on 1.3 GHz superconducting cavities developed by DESY
- Japanese Linear Collider / Next Linear Collider (JLC/NLC)
  - Based on 11.4 GHz normal conducting rf system promoted by SLAC and KEK
- Japanese C-band Linear Collider (JLC-C)
  - Based on 5.7 GHz normal conducting rf cavities developed at KEK
- Compact Linear Collider (CLIC)
  - Based on 30 GHz normal conducting rf using a Two-Beam rf generation concept developed at CERN
- TESLA and JLC/NLC are the primary designs aimed at the next facility – CLIC is further in the future

Why Linear Colliders?

- Clean collisions with e+/e-
  - Point-like particles $\Rightarrow$ precision measurements
  - Effective E_{cms} for p-p ~ E_{cms} / 10
- However e+/e- emit synchrotron radiation when deflected

$$U_0[GeV] = 8.85 \times 10^{-5} \frac{E^4[GeV]}{R[m]}$$

- The rf system must replace this energy loss
  - Optimized (high energy) storage ring cost and size scale as E^2
  - At 200 GeV: LEP = 27 km with 3.6 GV of rf
  - At 1000 GeV: VLEP = 600 km with 100 GV of rf
- Linear collider cost scales linearly with energy

Linear Collider Difficulties

- Energy: beams are accelerated to full energy each pulse
  - Need inexpensive and efficient rf systems

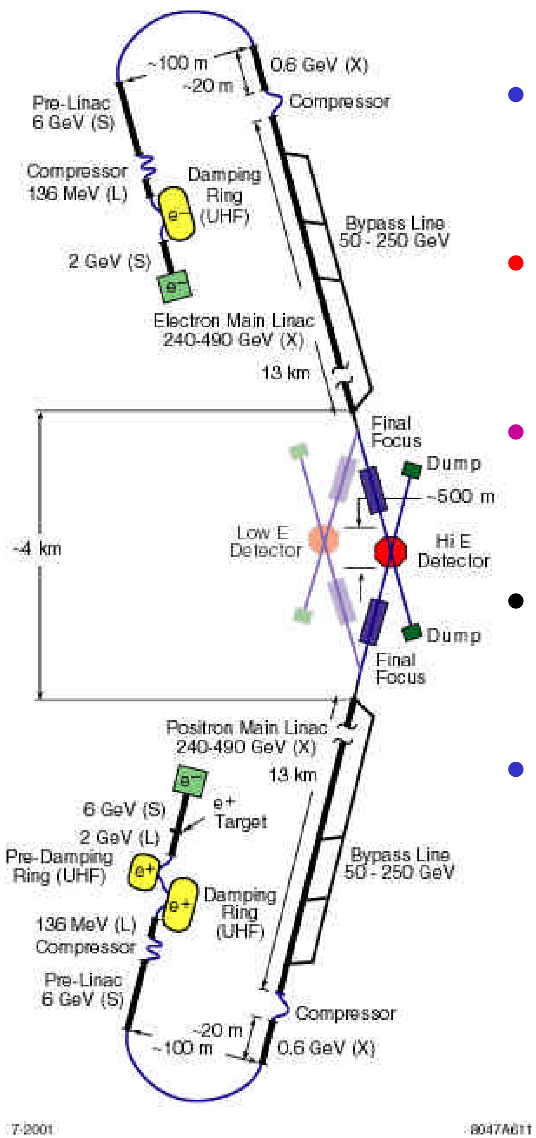
- Luminosity: linear colliders need very small spot sizes
  - Storage rings collide beams often
    - Low luminosity in each interaction
  - Linear collider rep rate is ~ 100 Hz versus 100 kHz
    - Extremely small beam sizes
  - Fortunately, the beam-beam tune shift is less important

$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y}$$

	Lum.	f_{rep}	n_b	$N[10^{10}]$	σ_x [μm]	σ_y [μm]
NLC	2×10^{34}	120 Hz	192	0.75	0.25	0.003
SLC	2×10^{30}	120 Hz	1	4	1.5	0.7
LEP2	5×10^{31}	10 kHz	8	30	240	4
PEP-II	3×10^{33}	140 kHz	1700	4	155	6

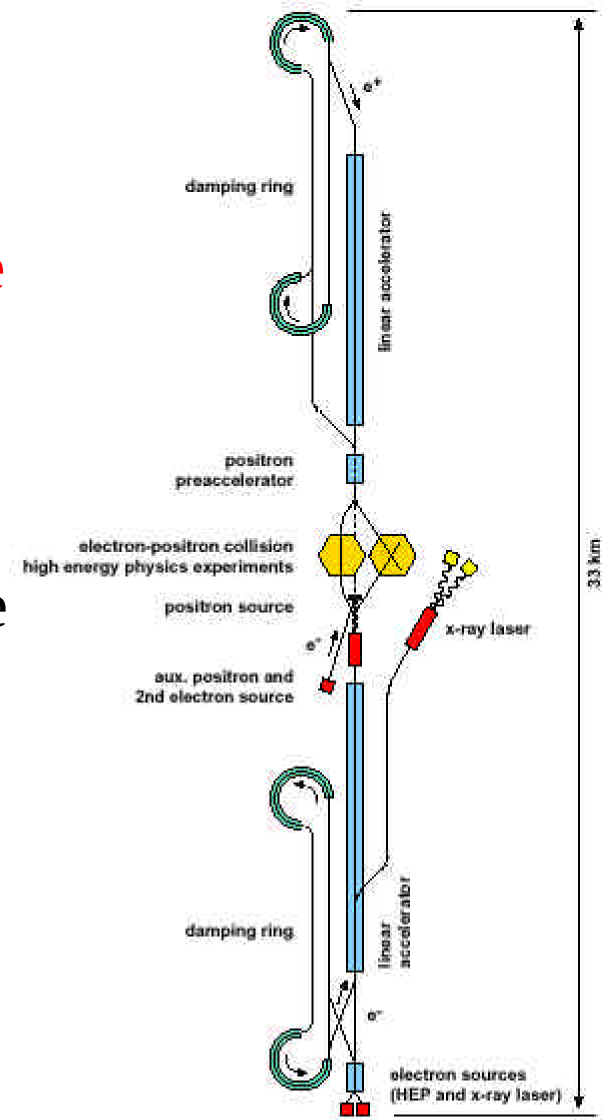
nanometers

The Pieces of an LC



- Particle sources to produce e+ and e- beams
- Damping rings to reduce the beam phase space
- Bunch compressors to shorten the bunch length
- Main linacs to accelerate the beams to the final energy
- Beam delivery system to collimate the beam tails and focus the beams to nanometer spot sizes

Drawings not to scale!



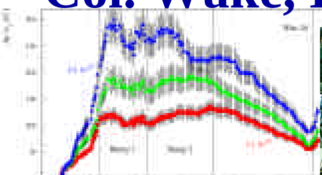
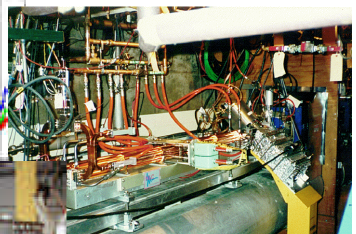
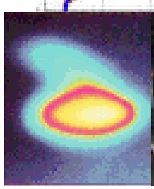
Experimental Basis for a Linear Collider

SLC and FEL's

Bunch Comp.

SLC, FFTB, ASSET, Col. Wake, E-158

ε preservation

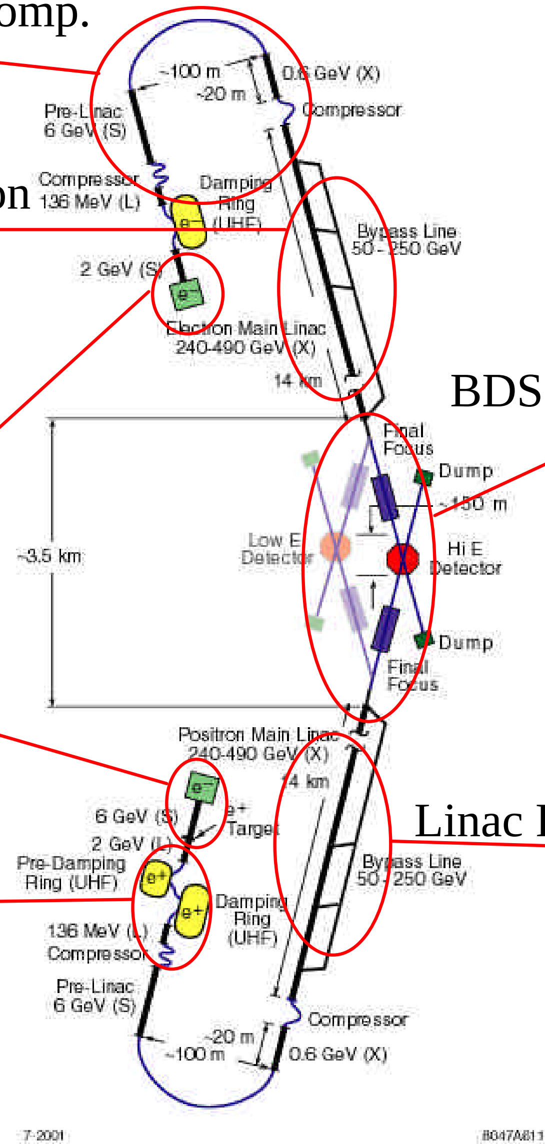





SLC, E158, Nagoya Univ.

e+ / e- sources

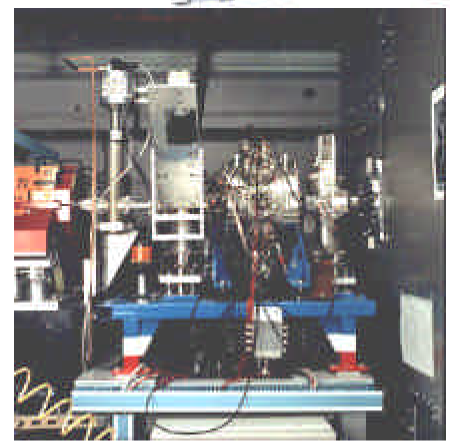

ATF, 3rd gen. SRS, SLC

DR's

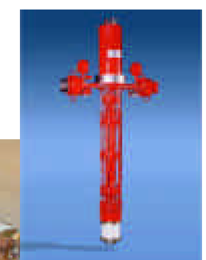
SLC and FFTB

BDS & IR

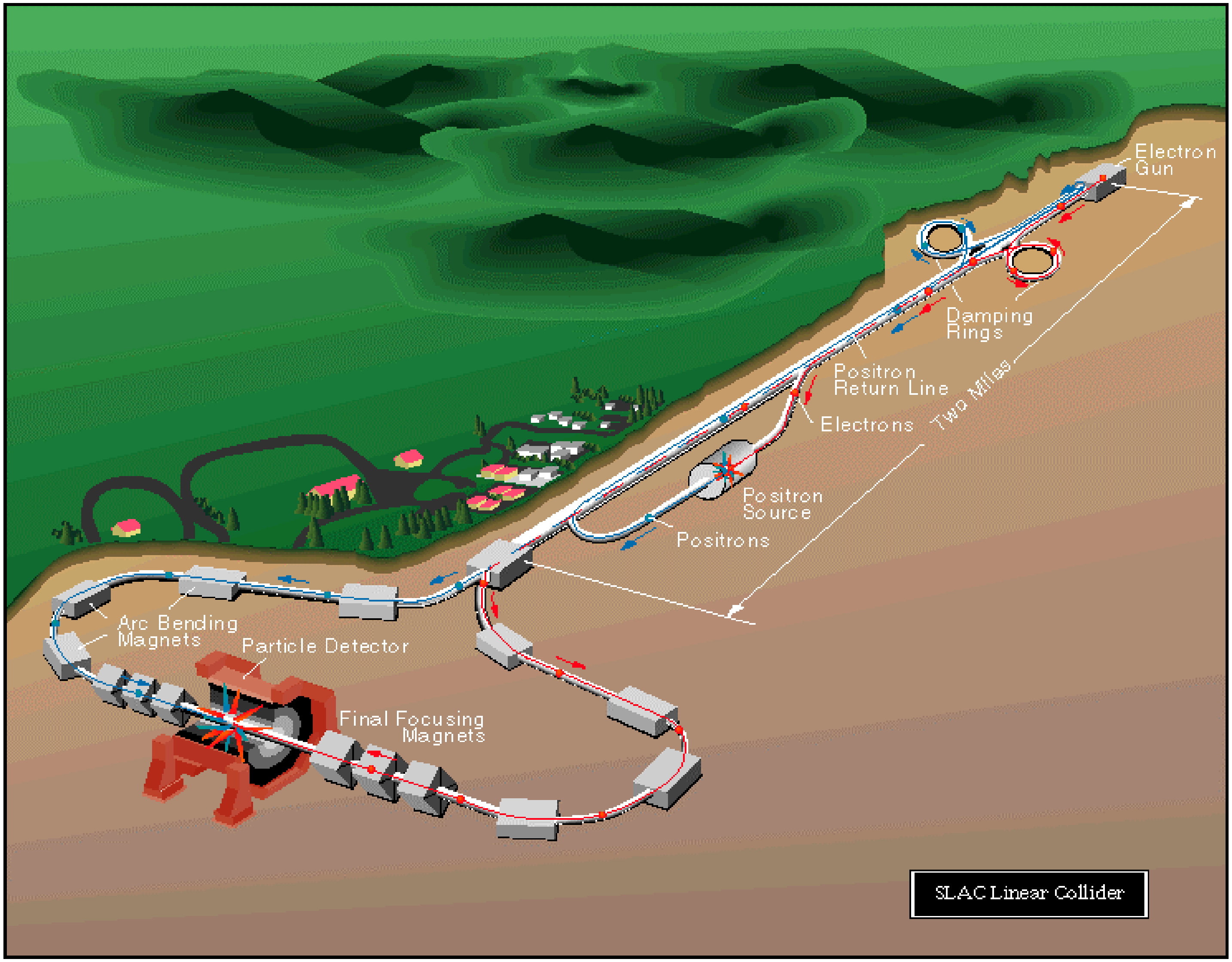


KEK and SLAC X-band RF
DESY SC RF

Linac RF



First Linear Collider: SLC



Built to study the Z^0 and demonstrate linear collider feasibility

Energy = 92 GeV

Luminosity = 2e30

Has all the features of a 2nd gen. LC except both e+ and e- used the same linac

A 10% prototype!

Luminosity Issues
Only few x 10,000 larger than SLC!

$$L = \frac{f_{rep}}{4p} \frac{n_b N^2}{s_x s_y} H_D \quad \Longrightarrow \quad L = \frac{2P_b}{4p\ E_{cms}} \frac{N}{s_x s_y} H_D$$

- Increased beam power from long bunch trains
  - SLC: 120 Hz x 1 bunch @ $3.5\text{x}10^{10}$
  - NLC: 120 Hz x 192 bunches @ $0.75\text{x}10^{10}$ → 200x (TESLA ~ 340x)
  - Generation of uniform multi-bunch trains sets source requirements
  - Control of long-range wakefields is essential to prevent BBU

- Larger beam cross-sectional densities: N / (σ_x σ_y)
  - SLC: $3.5\text{x}10^{10}$ x 1.6 μm x 0.7 μm (FFTB: $0.6\text{x}10^{10}$ x 1.7 μm x 0.06 μm)
  - NLC: $0.75\text{x}10^{10}$ x 250 nm x 3.0 nm → 330x SLC (TESLA ~240x)
  - Factor of 5 from energy (adiabatic damping) and factor of 4 from stronger focusing (similar to Final Focus Test Beam)
  - Factor of 15 ~ 30 from decrease in beam normalized emittances at IP

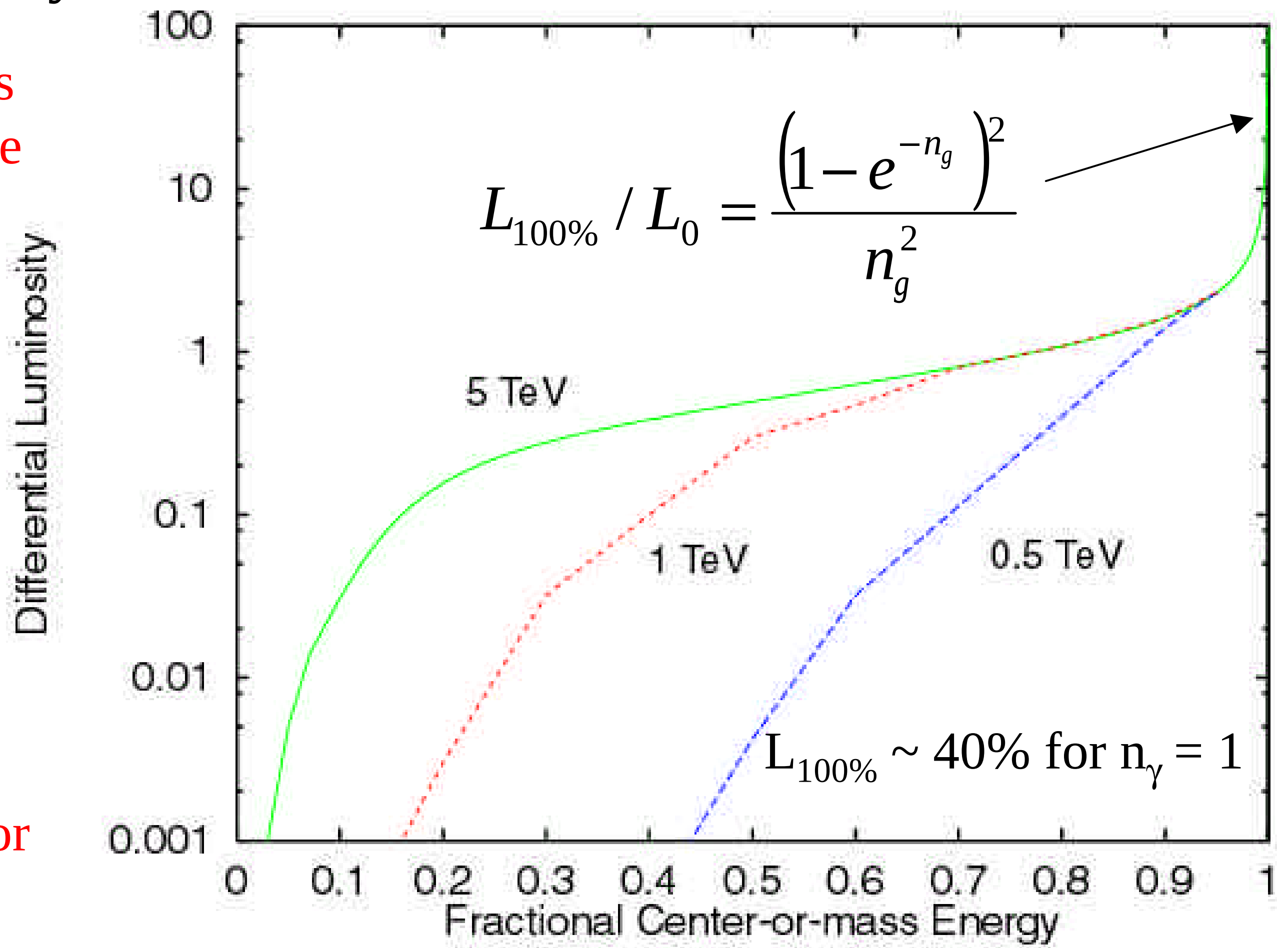
  ⇒ Damping rings and Low Emittance Transport

Primary Issues for the LC

- Two issues for linear collider R&D: energy and luminosity
- RF systems
  - Modulators, klystrons, cavities and test facilities
- Luminosity issues
  - Damping rings and sources
  - Main linac dynamics and alignment
  - IP issues
- International organization – how to build a machine!
- Either TESLA or JLC/NLC collider could be built
  - different risks and different connections to the future

Luminosity Spectrum

- Luminosity requires forces choice of beam parameters
- Very strong beam-beam forces ⇒ large emission of beamstrahlung, i.e. synchrotron radiation due to beam fields
  - Forces ‘flat’ beams and limits b-b force
  - Spectrum is characterized with number of photons n_γ and average energy loss δ_B
  - Radiation regime is characterized with $Y - Y \ll 1$ for classical regime



Luminosity Formula

- IP effects force flat beams to minimize beam fields / luminosity
- The luminosity can be written:

3 terms to maximize L

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

  - P_{beam} is the average beam power ~ MW
  - N / σ_x is proportional to the backgrounds ~ 2×10^{14} cm^{-1} for $n_\gamma = 1$
  - σ_y depends on the vertical phase space: $\sigma_y = \sqrt{\varepsilon\beta} \sim 10^{-7}$ cm

- In this case, the luminosity can be expressed:

$$L \propto \frac{P_{beam}}{E_{cms}} \sqrt{\frac{1}{\gamma\varepsilon_y \beta_y}}\, n_\gamma H_D \qquad \text{or} \qquad L \propto \frac{P_{beam}}{E_{cms}} \sqrt{\frac{\delta_B \sigma_z}{\gamma\varepsilon_y \beta_y}}\, H_D \left(1 + (1.5\Upsilon)^{2/3}\right)$$

Beam Power

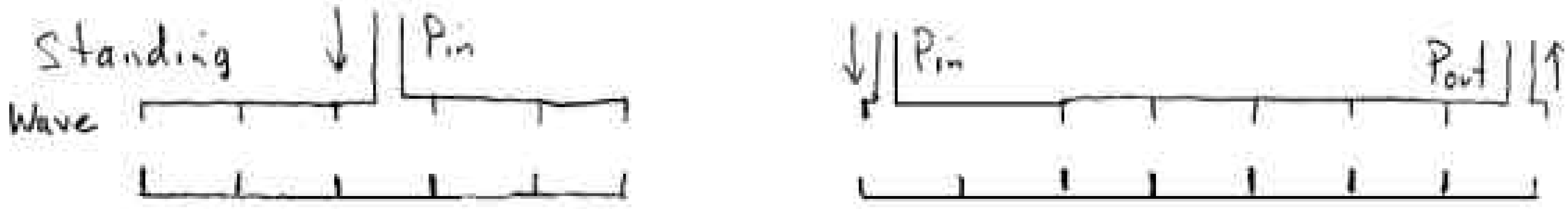
- Given MW's of beam power, we need efficient transfer from wall plug to the beam
  - $P_{beam} = P_{ac}\eta_{ac}\eta_{beam}$ Beam and cavity parameters

Money Rf technology (modulator, klystrons, and distribution)

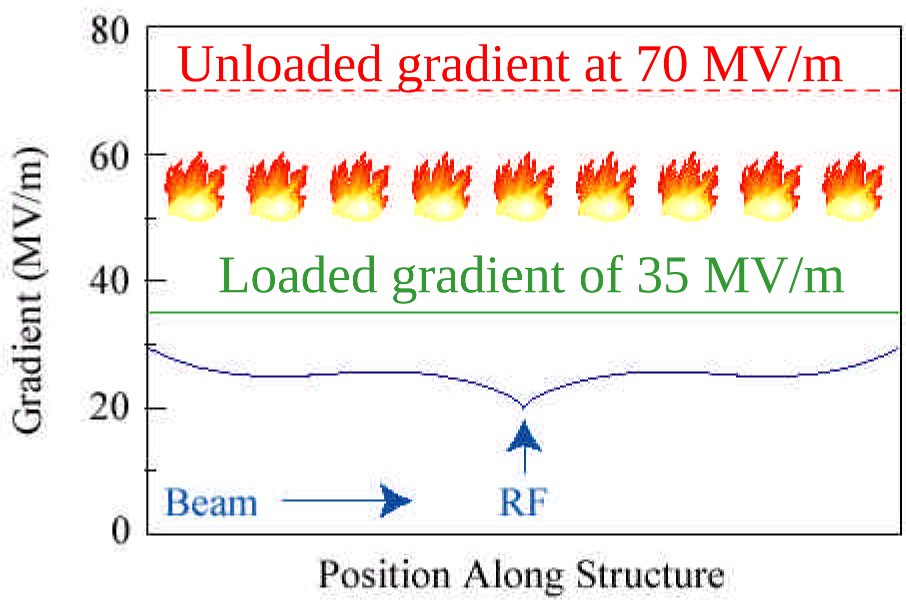
- In a superconducting system at 2°K, the power to remove the heat is ~ 600x the power lost at low temperature
- However, the superconducting cavities loose very little power to the cavity walls → higher η_{beam}
  - The very high cavities Q's allow for long low power rf pulses
    - These are easier to generate than short high power rf pulses
  - The long rf pulse requires a long beam pulse
    - These are harder to generate in the particle sources and damping rings

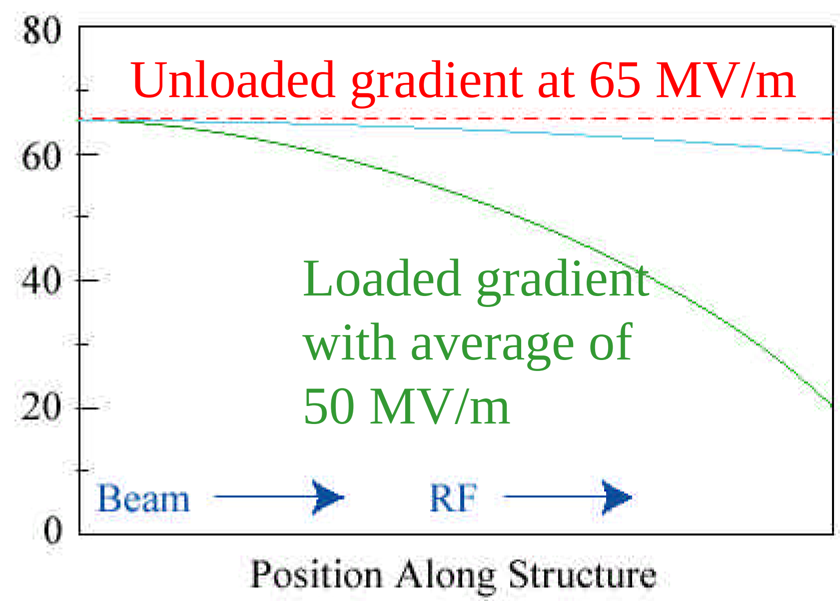
Standing Wave vs. Traveling Wave

- There are two type of rf cavities: standing wave and traveling wave:



  - Both types of cavities are most efficient when $V_{beam} = ½\, V_{cav}$





RF Cavities

- Fields are established in cavities after a cavity filling time
- In steady state, power into rf cavities goes to the beam, the cavities walls, and (for traveling wave) to the output coupler
- Beam current must be chosen to extract power before dissipation

$$h_{beam} = \frac{P_{beam}}{P_{beam} + P_{cav} + P_{out}} \frac{T_{beam}}{T_{fill} + T_{beam}}$$

$\approx$ 1 TESLA
$\approx$ 0.5 NLC

$\approx$ 0.67 TESLA
$\approx$ 0.8 NLC

	TESLA SC Cavities	NLC NC Cavities
Q	10^{10}	5000
Shunt imp. R_s	10^{13} Ω/m	80 MΩ/m
P_{cav}	60 W/m	30 MW/m
P_{beam}	~250 kW/m	~50 MW/m
I_{beam}	10 mA	1 A
T_{fill}	420 μs	120 ns

($P_{beam} > P_{cav}$)

Linear Collider RF Systems

- The RF systems consist of 4 primary components:

η_{ac}

Modulators:

line ac → pulsed dc for klystrons

TESLA distributes pulse dc (12 kV) in long 2.8 km cables

NLC needs 500 kV / 250 A per klystron

Klystrons:

dc pulse → rf at 1.3 or 11.424 GHz

TESLA multi-beam klystron delivers 10 MW / 1.5 ms

NLC klystron delivers 75 MW / 1.6 μs

RF distribution:

transport rf power to accelerator structures

TESLA needs couplers and circulators on each structure

NLC compress klystron power to increase peak power

η_{beam}

Accelerator Structures:

→ power to beam, prevent dipole mode instabilities

RF Pulse Format

- TESLA rf pulse: 5 Hz with 5 x 10^{-3} duty cycle

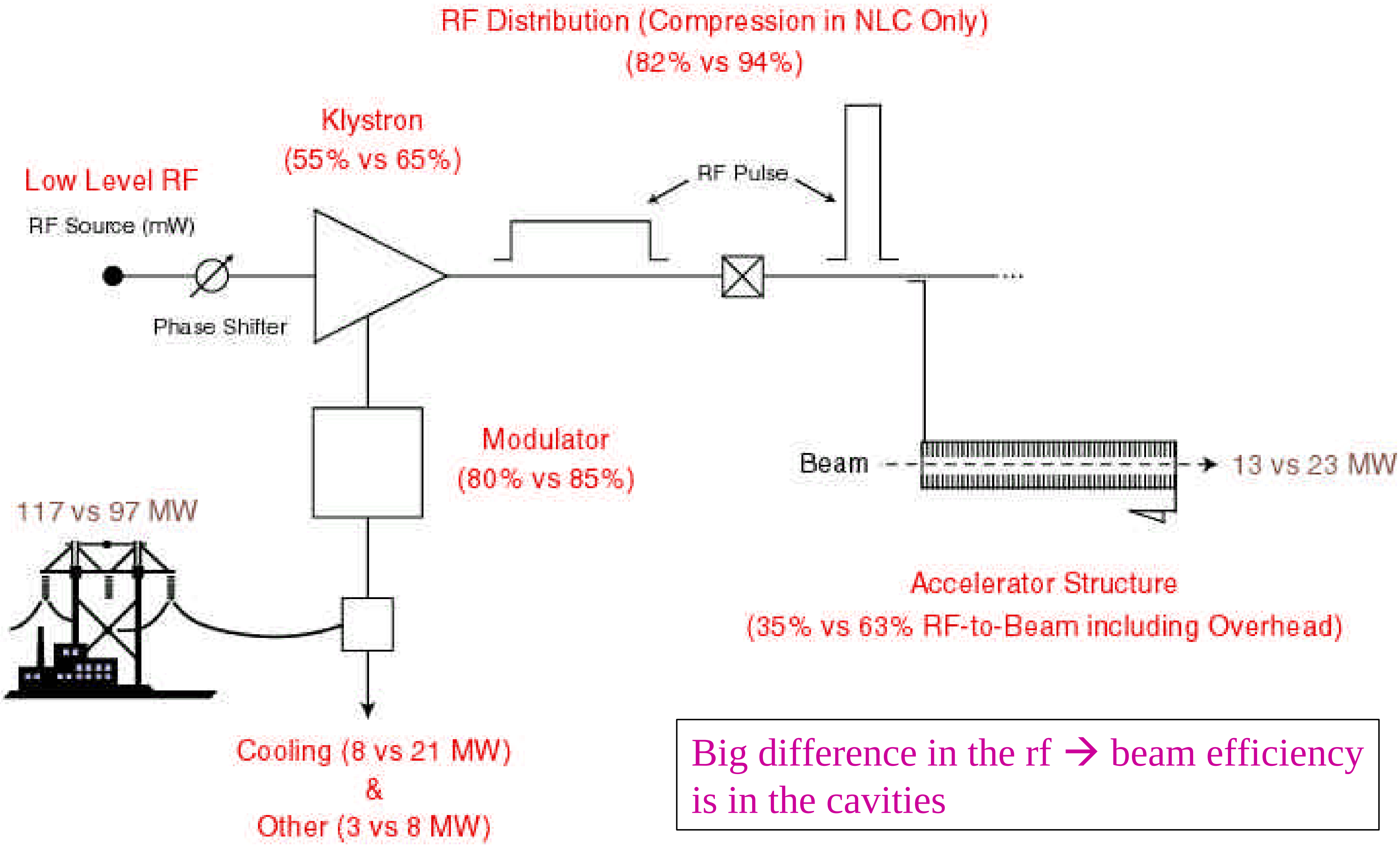
Modulator	1.4 ms	1600 A	12 kV	26 kJ
Klystron	1.4 ms	130 A	115 kV	10 MW
Structure	1.4 ms	250 kW		

- NLC rf pulse: 120 Hz with 3 x 10^{-5} duty cycle

Modulator	1.6 us	2000 A	500 kV	1.6 kJ
Klystron	1.6 us	250 A	490 kV	75 MW
Pulse Comp	1.6 us 150 MW --> 400 ns x 450 MW			
Structure	396 ns	75 MW		

- The shorter pulses deliver smaller energy per pulse but higher peak power

RF System Schematic



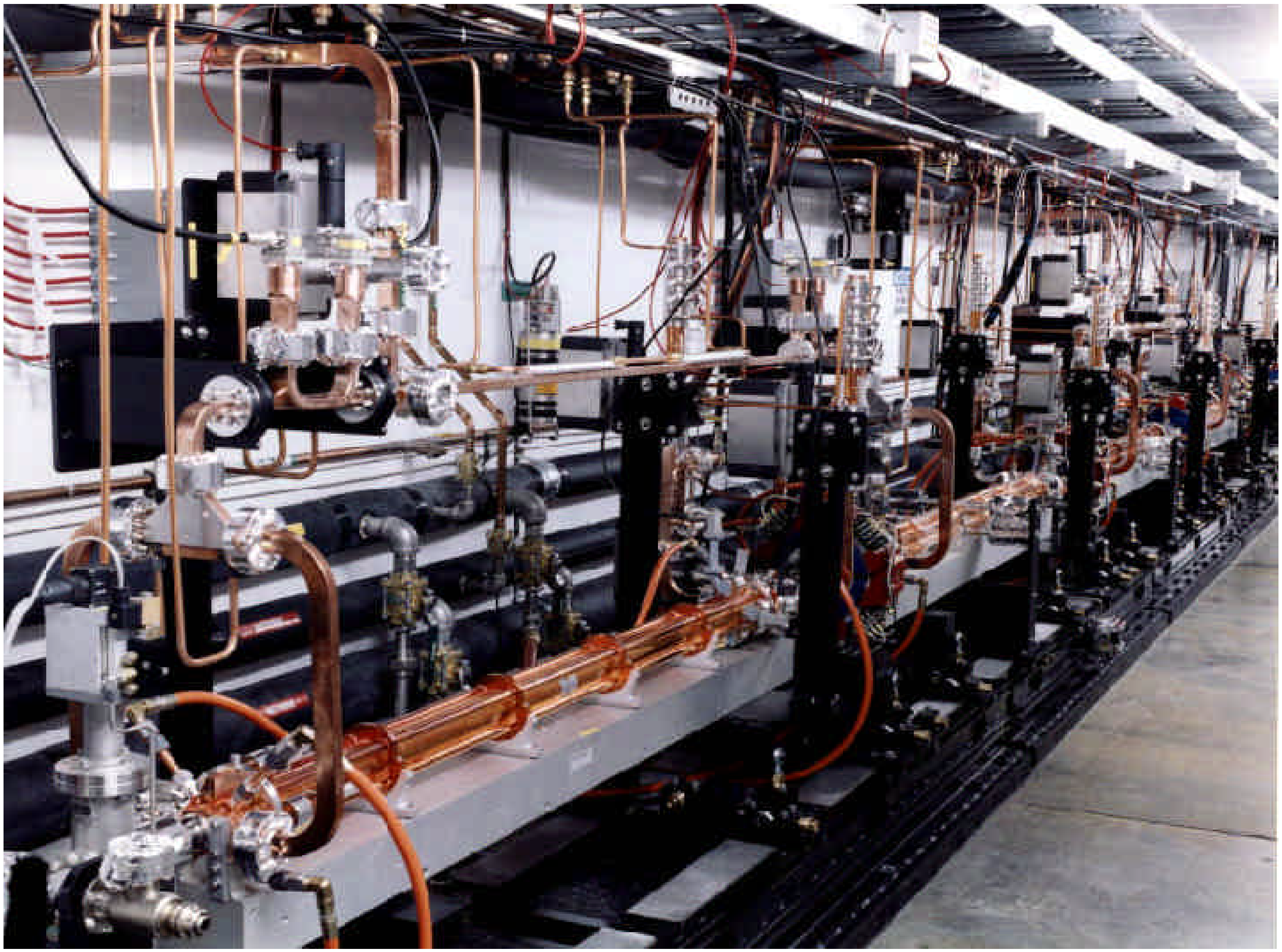
Big difference in the rf → beam efficiency is in the cavities

RF Cavities (Again)

- Superconducting cavities have roughly 2x higher η_{beam} allowing for higher beam power
  - Potentially, the higher beam power could turn into higher luminosity **however** other beam dynamics effect reduce this gain
- Low frequency SC cavities also have lower wakefields
  - This implies looser alignment tolerances which might yield smaller IP spot sizes **however** the looser alignment is also more difficult to attain in the cryostats
- Normal conducting cavities have higher gradients
  - This could reduce the cost of the linear collider

- In both the SC and NC cases, the desired cavity gradients have not yet been attained
  - Extensive R&D programs aimed at gradients at SLAC and DESY

NLC Test Accelerator (X-band)



Operated since 1996

~350 MeV

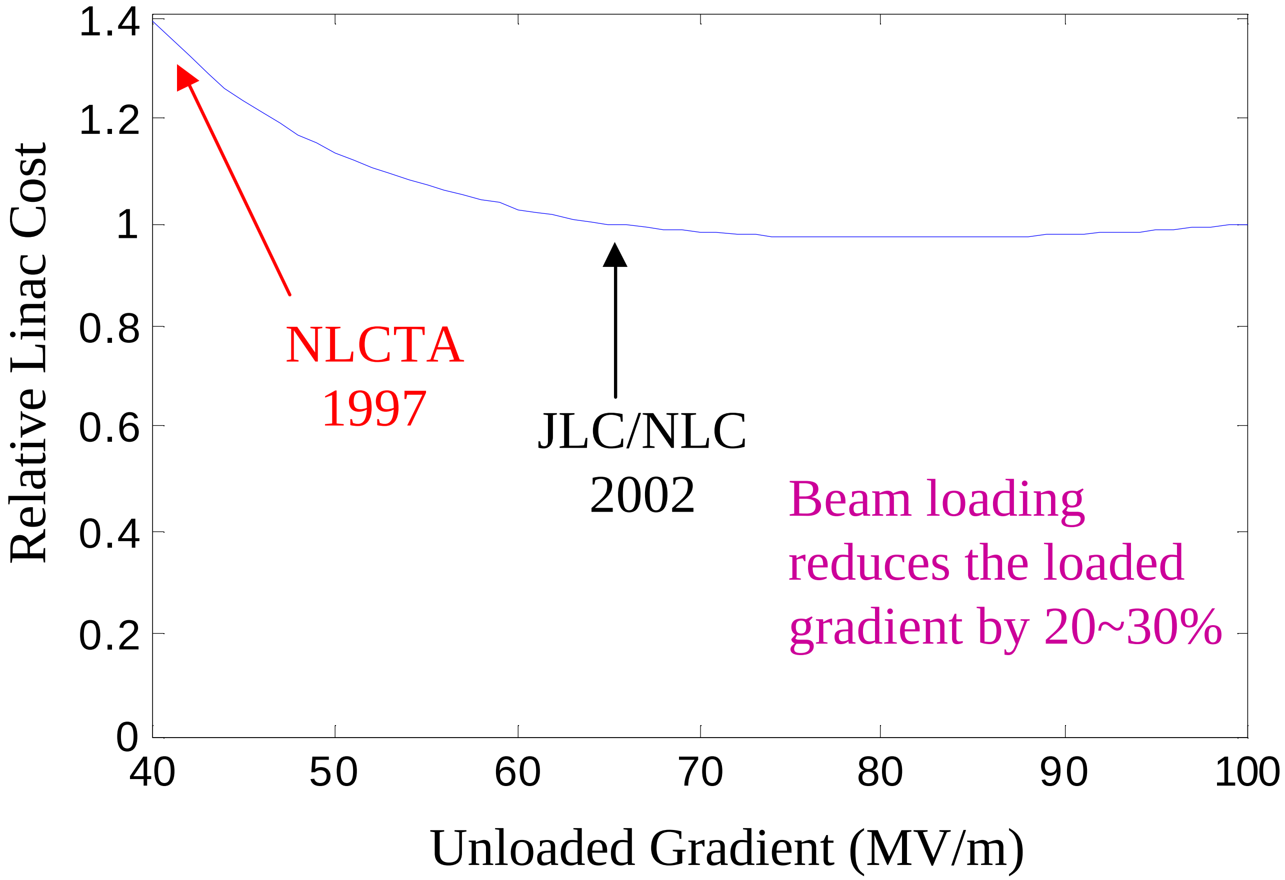
5000 hrs per year presently

NLC-ZDR rf system from 1996:

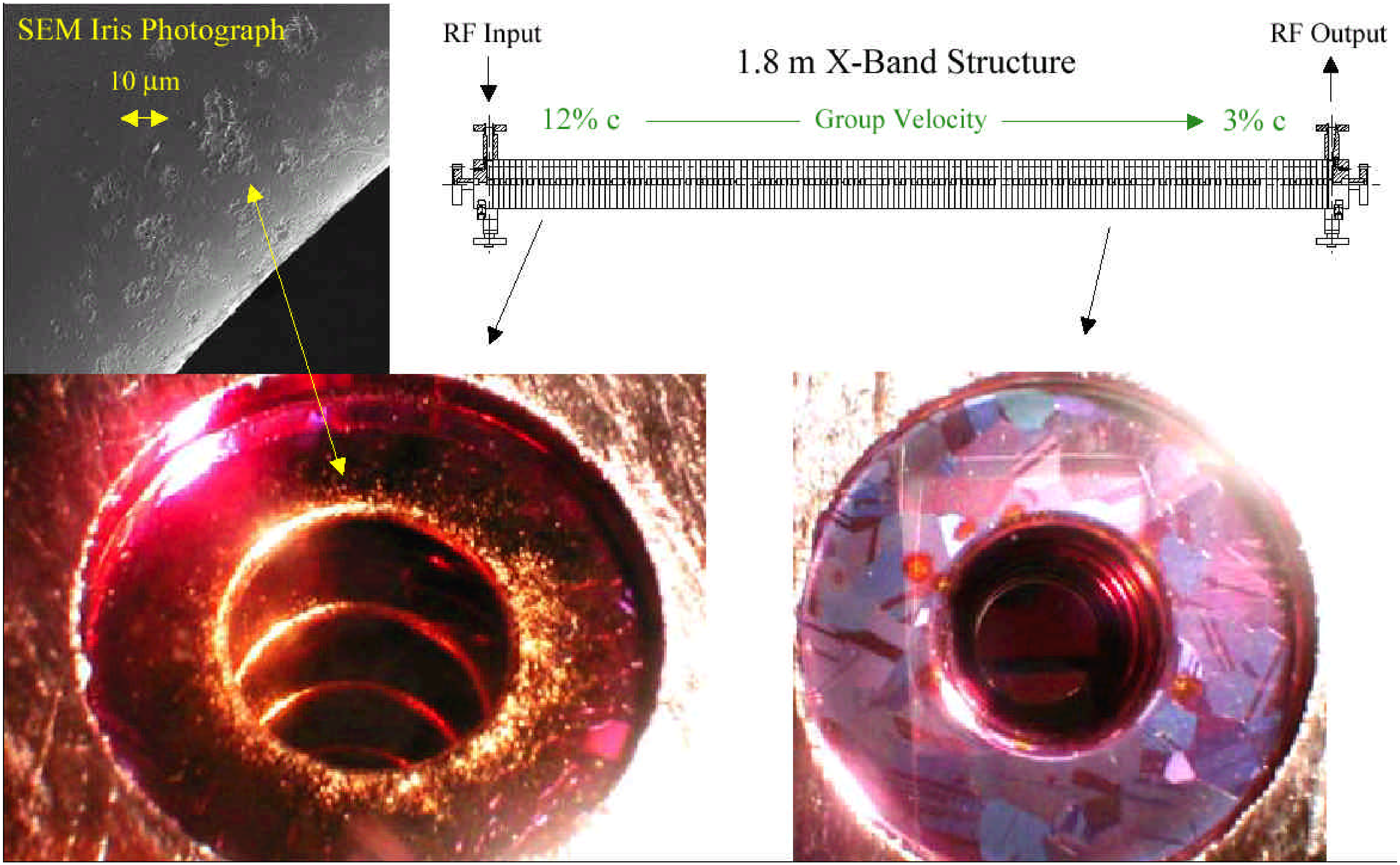
- Five 50MW klystrons
- 3 SLED-II's
- 4 1.8 m long structures

Gradient Choice: 65 MV/m

- NLCTA operated at 40 MV/m in 1997
  - Why all the effort to push to higher gradients?
  - Two reasons: the **linac cost** and **future expandability**

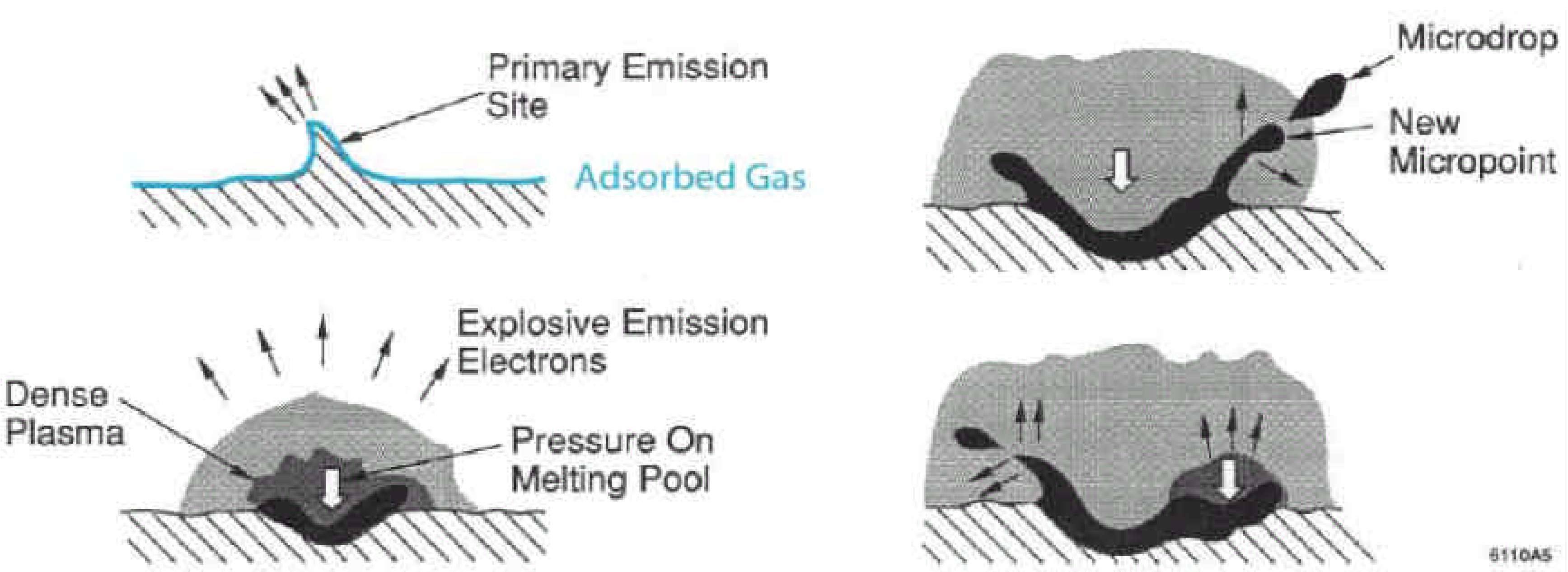


Damage in 1.8-m Structures



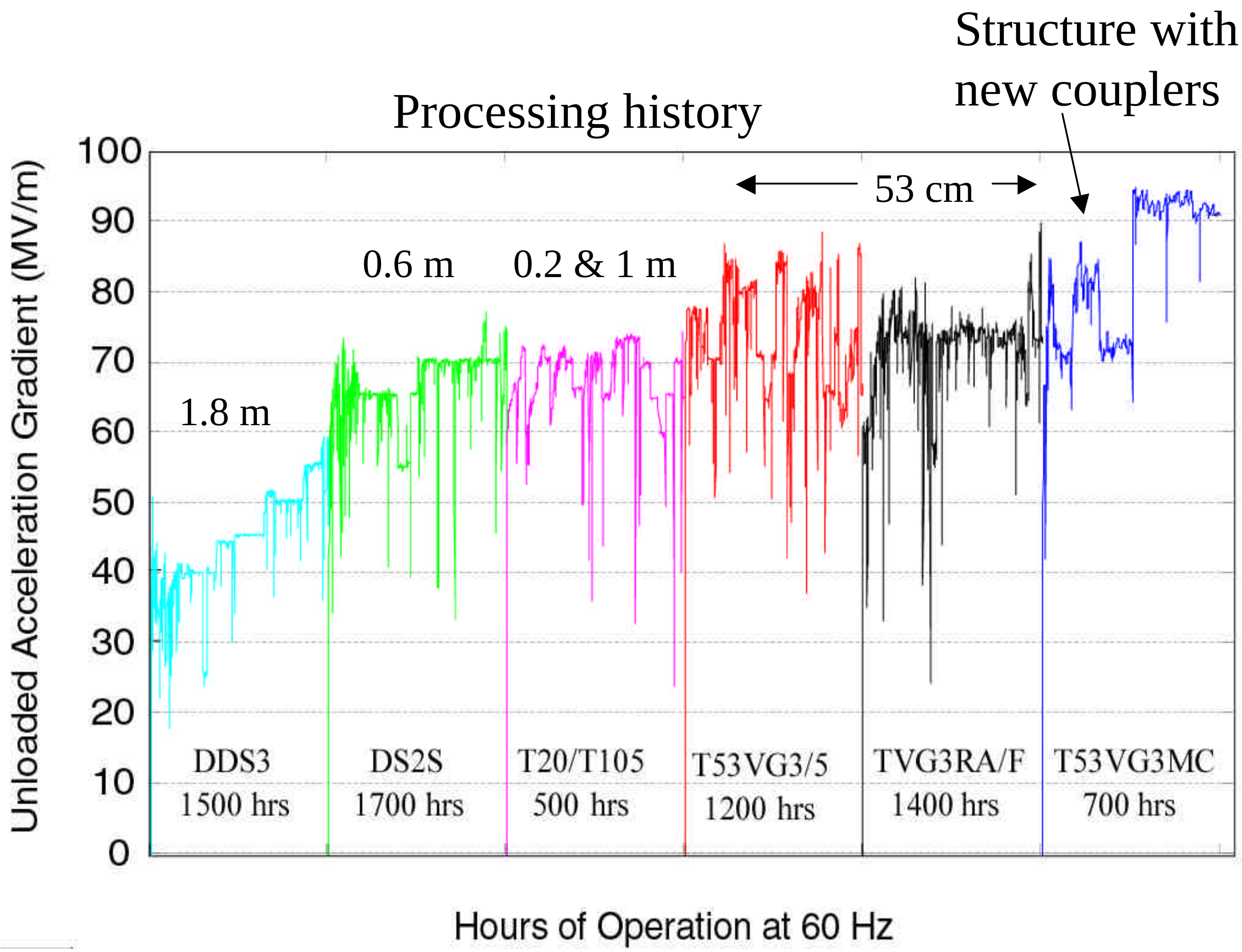
RF Processing/Breakdown Model

- RF processing can melt field emission points → higher fields
  - This is good!
- However, if too much energy in the breakdown event:
  - Electrons generate plasma and melt surface; with enough energy, molten surface splatters and generates new field emission points!
  - This is bad!



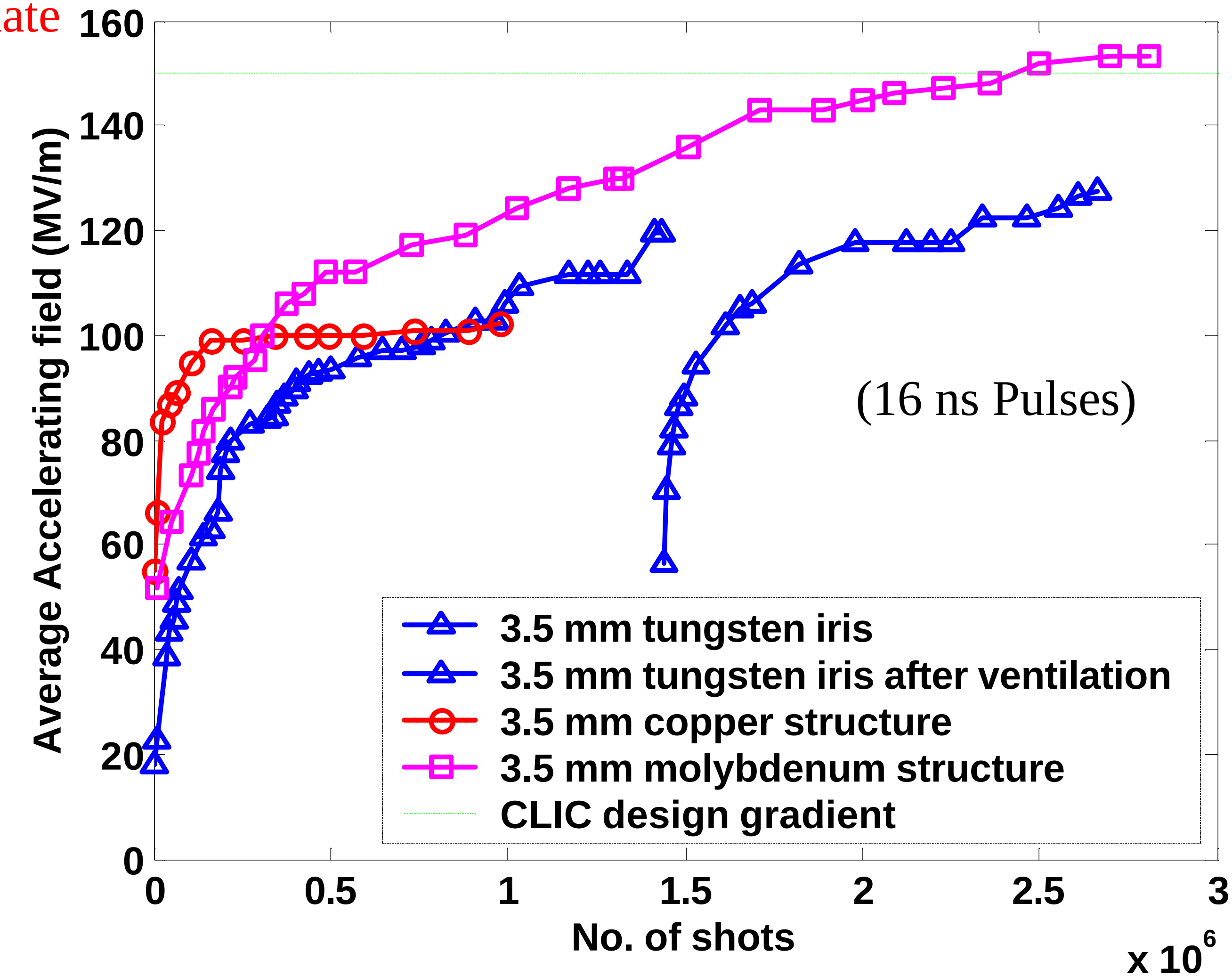
JLC/NLC Structure Testing

- Test structures rapidly process to ~70 MV/m
- New coupler greatly improves performance
- However test structures apertures are too small for NLC operation
- NLC prototype structures are being tested



CLIC Structure Testing

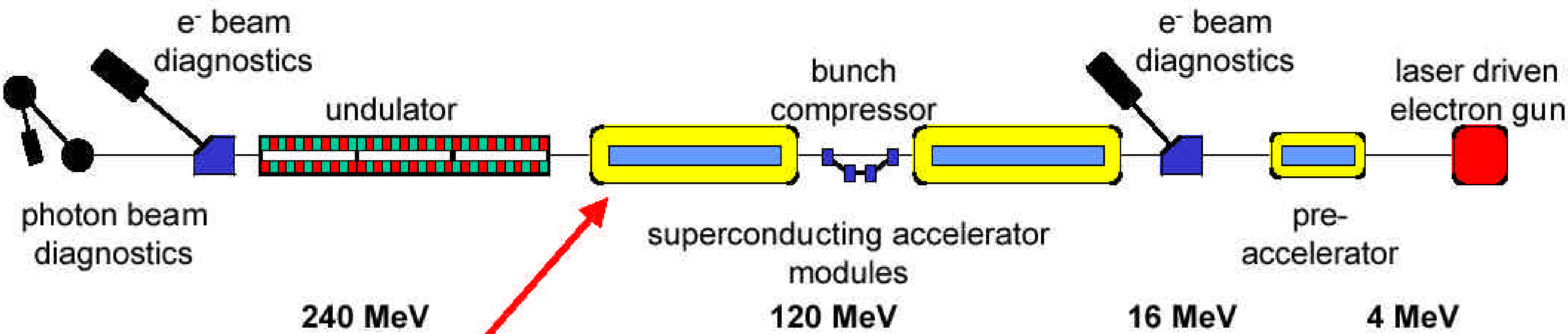
- CLIC has a higher design gradient
  - Studying alternate materials such as Moly and Tungsten
  - ~50% higher gradient
  - Need to test with longer pulses but looks promising!
  - Will bring a structure to NLCTA

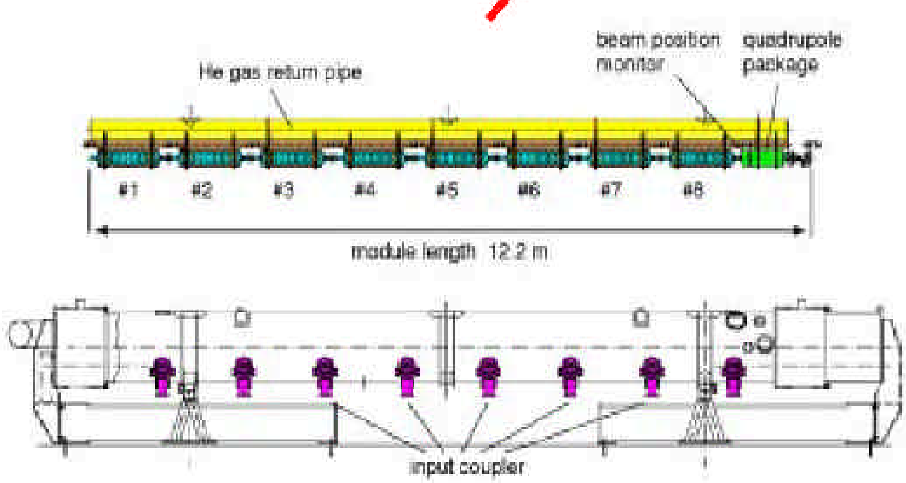


History and DESY Challenge

- Historically, the main drawback of pulsed superconducting accelerating structures has been the low gradient of the cavities combined with the high cost of cryogenic equipment.
  - At the time of the first TESLA workshop pulsed superconducting RF cavities in particle accelerators were usually operated in the 5 MV/m regime
- Increase the design gradient by a factor of 5 to 25 MV/m
  - New materials specification; new cleaning and fabrication techniques; new processing techniques
- Reduce the cost per unit length of the linac by a factor of 5
  - Applying economical cavity production methods and by assembling many cavities in a long cryostat.

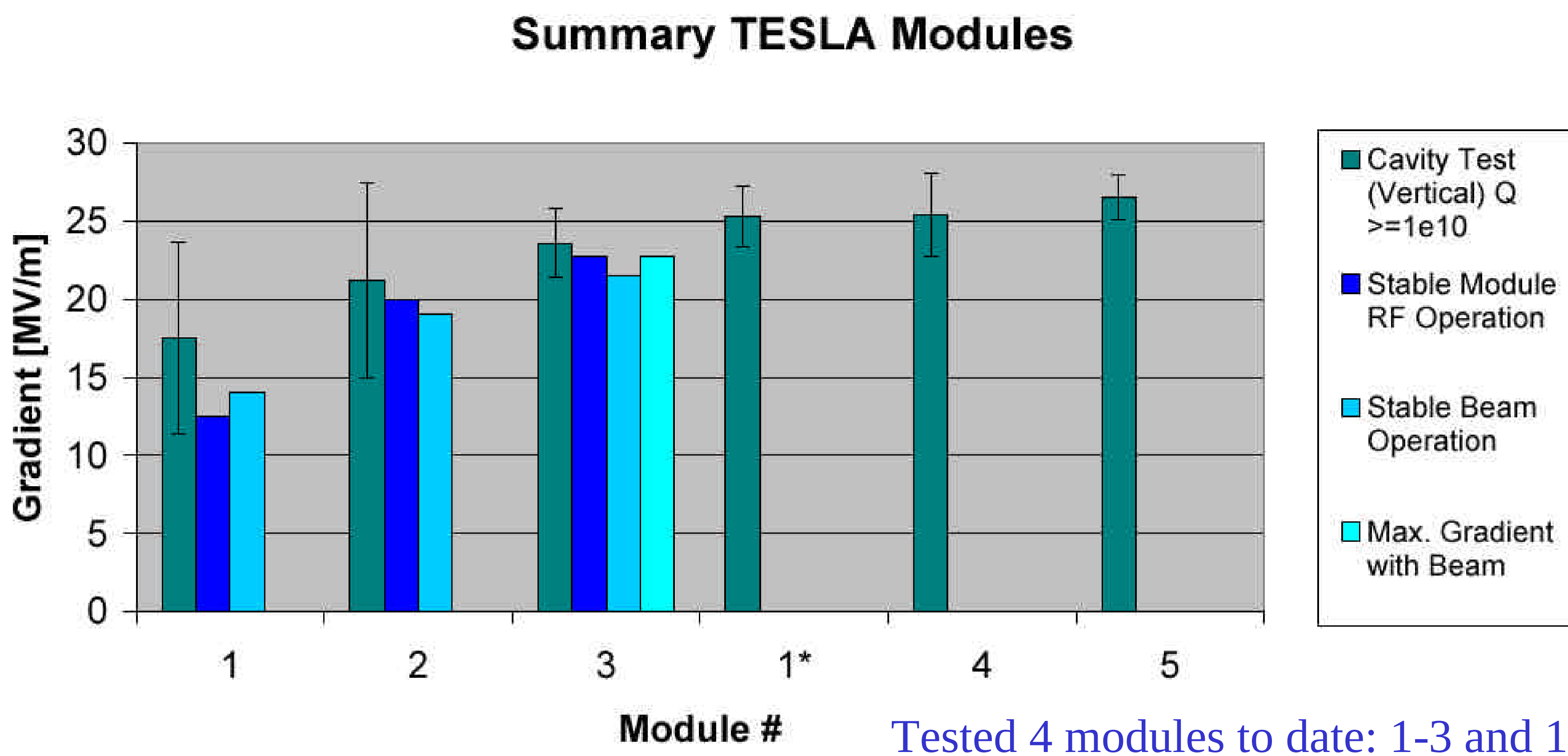
TESLA Test Facility Linac





TESLA Module Testing

			1	2	3	1*	4	5
Cavity Test (Vertical) Q >=1e10	cw	several hours	17,5	21,2	23,6	25,3	25,4	26,5
Sigma			6,18	6,28	2,21	1,98	2,7	1,4
Stable Module RF Operation	10Hz, 800 mus	several days	12,5	20	22,7			
Stable Beam Operation	1 Hz, 800 mus	6 days			21,5			
	1 Hz, variable pulse length		14	19				
FEL Operation	1 Hz, variable pulse length	10000 hours		14	14			
Max. Gradient with Beam	1 Hz, 800 mus				22,7			



Tested 4 modules to date: 1-3 and 1*

Recent Module Testing Results

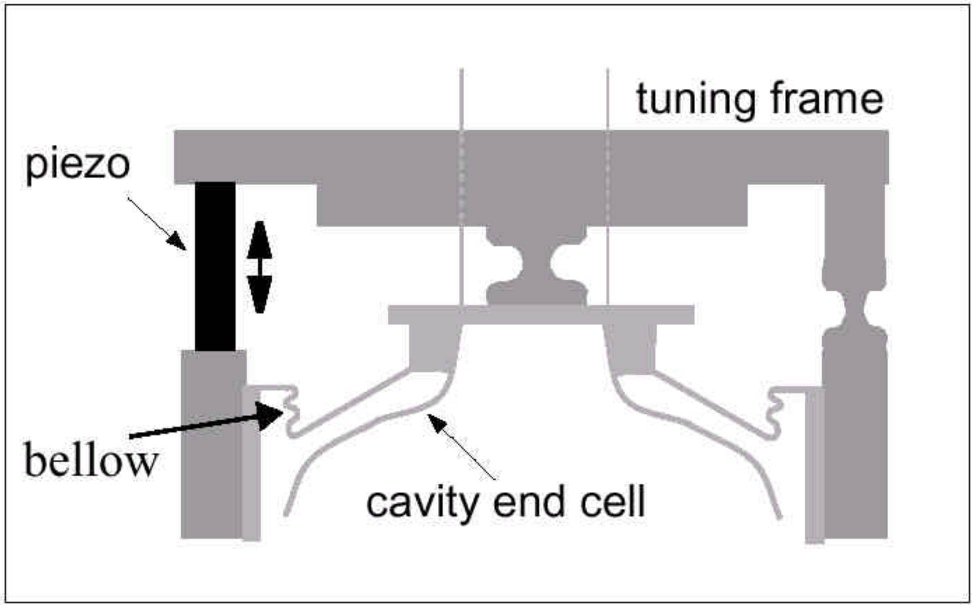
- Module 3 and 1* are the latest two modules
  - Both were tested in Linear Collider mode with long pulses and high gradient
  - Module 3 accelerated beam
  - Module 1* had two poor cavities – trying find reason
  - TESLA 500 goal 23.8 MV/m which is close

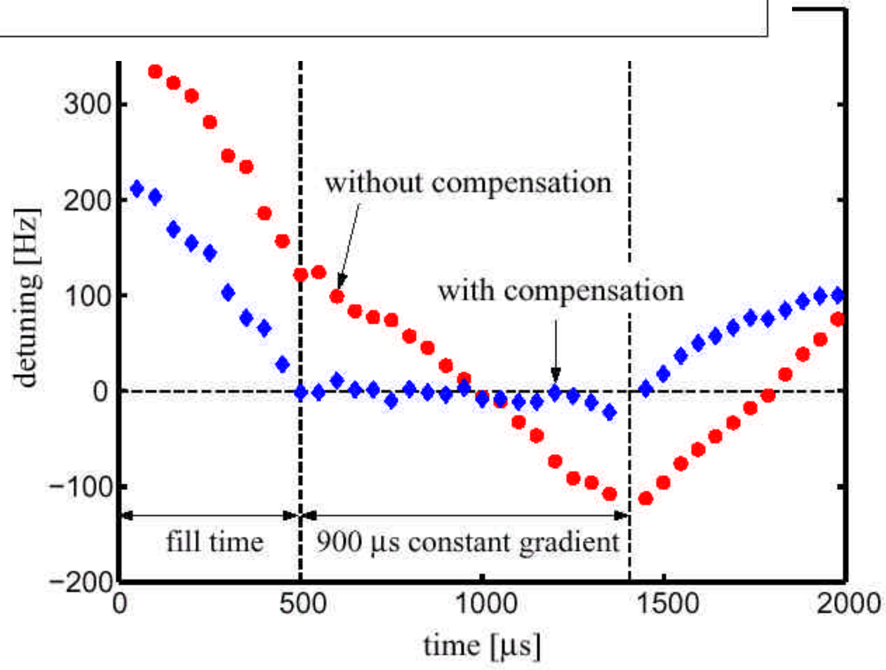
	Cavity #	#1	#2	#3	#4	#5	#6	#7	#8	Ave.
Module 3:	Single cell	22.7	27.0	25.0	25.0	26.3	30.3	28.5	18.4	**25.4**
tested Nov.	Peak rf									**23.7**
1999 and	Stable rf	21.8	24.8	23.4	23.5	22.2	25.2	23.9	17.0	**22.7**
Apr. 2002	1 Hz beam	19.9	22.3	23.2	22.3	23.1	23.7	22.7	14.1	**21.4**
Module 1*:	Single cell	23.4	19.4	25.5	28.1	29.1	20.1	25.9	24.0	**24.4**
tested Oct.	Peak rf	21.8	18.0	25.3	27.0	27.1	17.9	24.9	22.1	**23.0**
and Nov.	Stable rf									**22.0**
2002										

Based on rf power measurements – beam measurements are ~5% lower at both NLCTA and TTF

Lorentz Forces

- Lorentz forces will deform the cavities causing a frequency shift: $\Delta f \sim G^2$
  - Problem at 35 MV/m although larger problem at the SNS
- Compensate with piezo-electric tuner added to main tuning assembly
- First tests were very successful

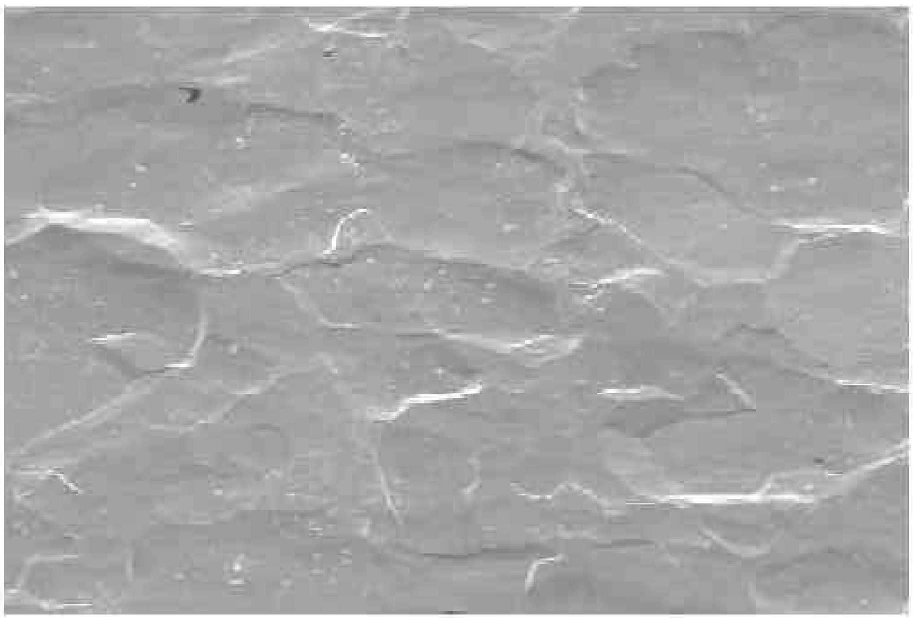




ElectroPolishing

Improvement of Nb surface quality with electropolishing

(CERN/KEK/Saclay/DESY)



before

After EP

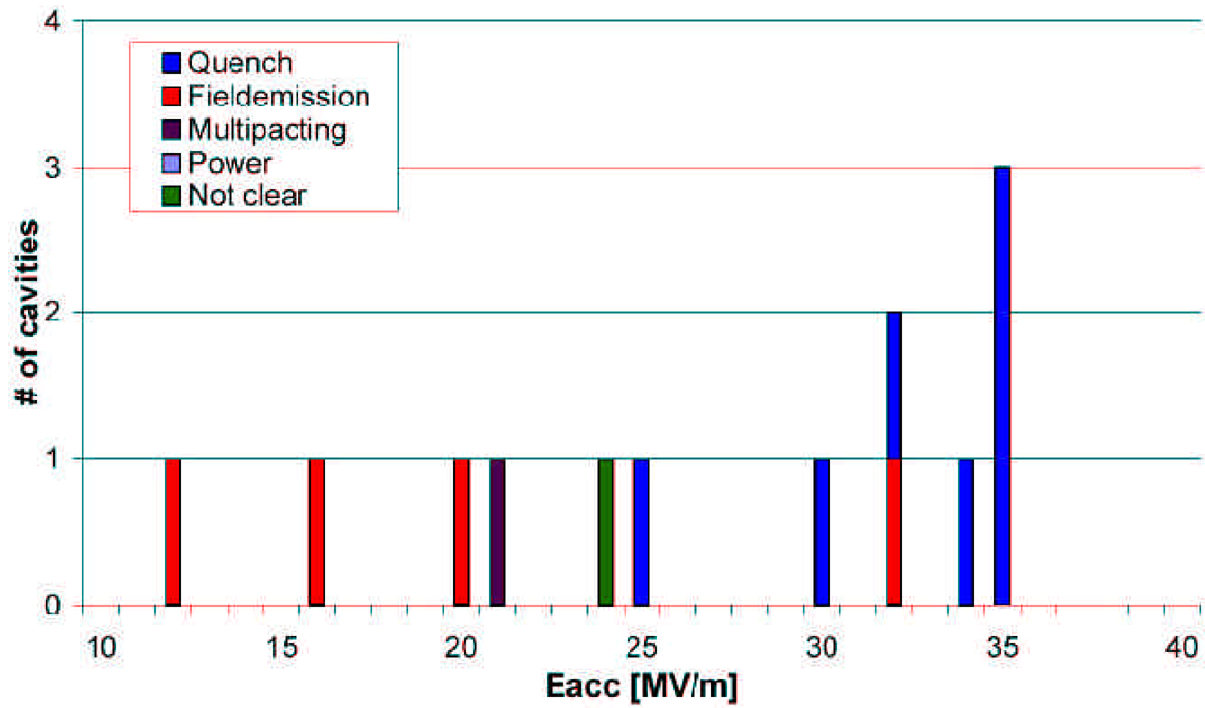
Performance of EP 9-Cell Cavities

Single cell cavities now reliably achieve gradients above 35 MV/m.

Transition from single-cell results to multicell cavities successful.

High gradient reproducibility in EP multicell cavities needs more work.

⇒ EP setup at DESY.

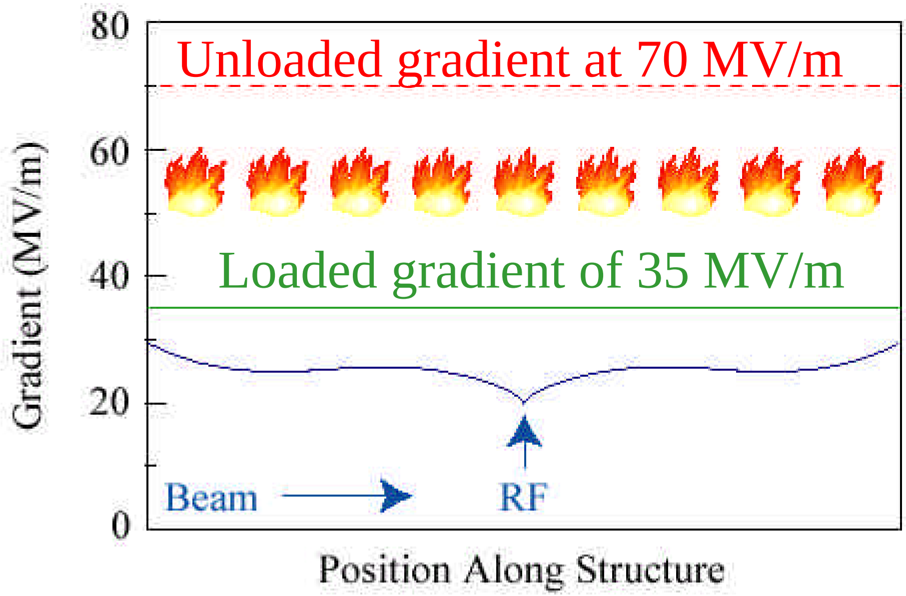


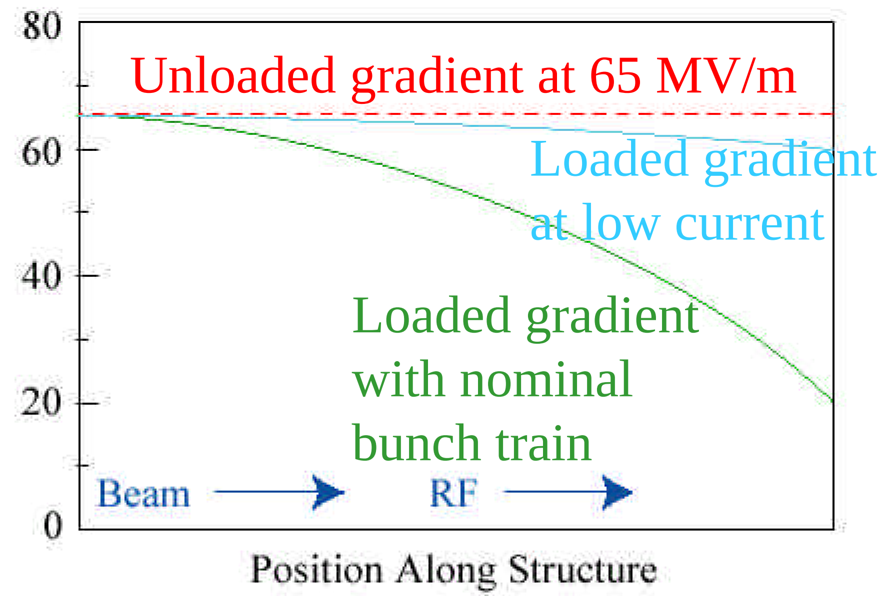
Desired Energy Range

- Would like to cover the Z-pole and W-production and then have continuous energy coverage at energies above LEP (>210 GeV)
- Upper energy reach needs are not known
  - Opinions vary around the world (HEPAP and ACFA specify 1 ~ 1.5 TeV while ECFA calls for 400 GeV 'with possible extension')
- Lower energy operation may be limited by e+ production
  - TESLA scheme does not work between cms energies of 200 to 300 GeV the range might be improved with modifications
- Highest energy reach can be attained by trading beam loading for energy
  - TESLA has 50% loading → 50% greater energy reach (***providing cavity limits are not exceeded***)
  - NLC has 35% beam loading – cavities are qualified at unloaded gradients → 35% greater energy reach

Energy Reach
Standing Wave vs. Traveling Wave

- The difficulty of qualifying the traveling wave structures at the full unloaded gradient can become a feature
  - Structures have capability of reaching full unloaded gradient at lower current where the loading is smaller





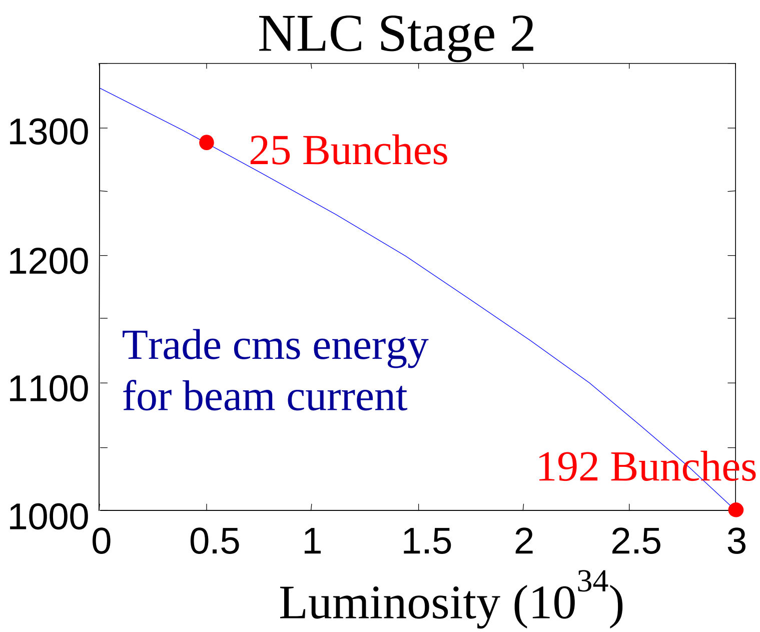
Energy Reach

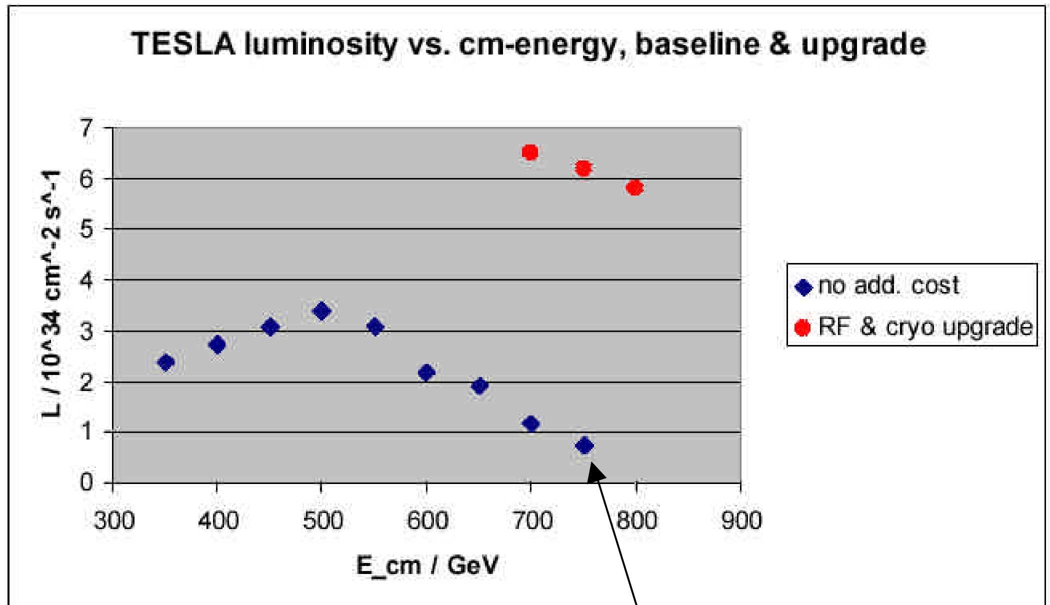
Both designs can trade luminosity for energy in Stage I

TESLA reaches ~ 750 GeV

NLC reaches ~ 650 GeV

JLC/NLC can do the same in Stage II to reach 1.3 TeV





Requires 35.7 MV/m

TESLA linac length would need to be increased by 80% to reach 1.3 TeV

Upgrade Routes and Costs

- NLC and TESLA costs are thought similar for 500 GeV
  - FNAL review of TESLA costing methods estimated 6.1 B$ with US accounting and 20% contingency
  - NLC costs are estimated at ~7 B$ with 30% contingency
  - The error on the costs is probably greater than any differences
- NLC upgrade requires adding structures, klystrons, etc. in the 2nd half of the linac tunnel
  - Cost to upgrade to 1 TeV is roughly 25% of initial TPC
- TESLA upgrade route: install 35 MV/m cavities at onset, double rf system, upgrade cryo-plant
  - Assuming initial installation of 35 MV/m cavities, cost to upgrade to 800 GeV cms is 20% of initial project cost
  - Upgrade from 800 GeV to 1 TeV is another 25% for a total of 45% of the initial project cost

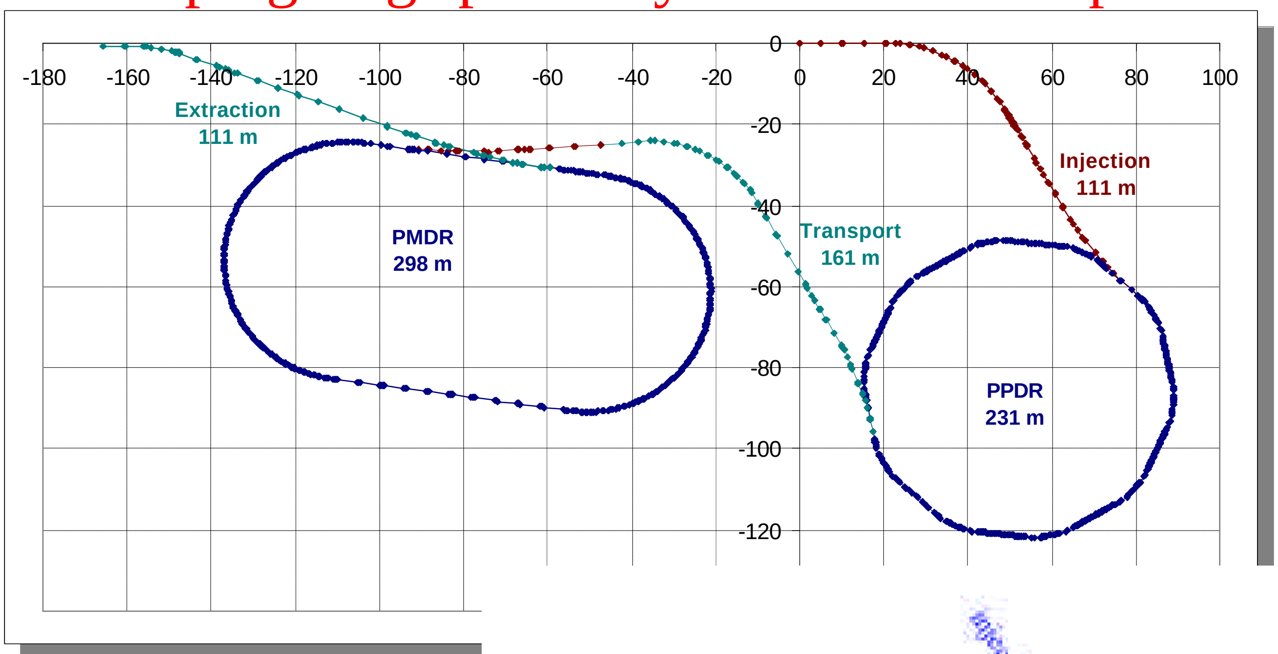
Non-RF Differences Driven by SC System

- Long pulse in SC design:
  - Large number of e+ per pulse
    - May prevent use of a conventional e+ source
    - TESLA design assumes an undulator-based e+ source
  - Very large damping ring complex with fast kickers
    - TESLA linac bunch train is ~300 km long
    - Train is compressed into the rings using high speed kickers
  - Reasonable intra-train feedback to correct for beam motion
    - Feedback speed is ~3 MHz
    - Harder to stabilize components in cryostats
- Low rf frequency
  - Larger apertures and smaller wakefields
    - Looser alignment tolerances in linac but poorer diagnostic resolution
  - Low dark current threshold
    - No accelerator has operated in this regime

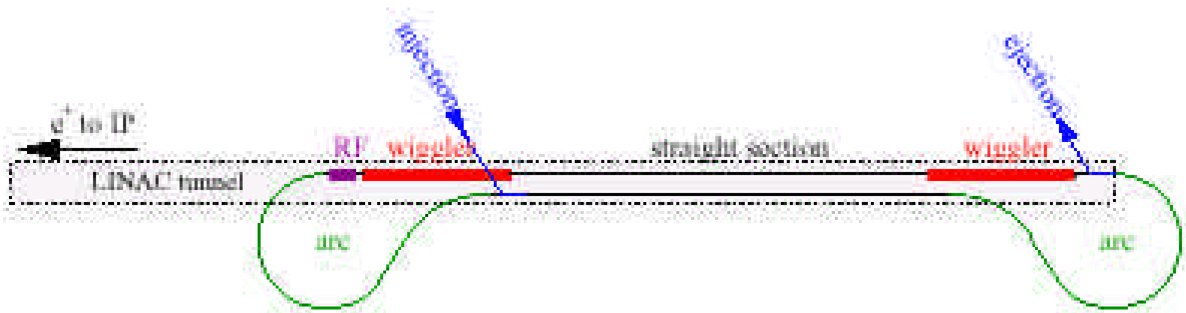
Damping Rings

NLC rings are similar to present generation of light sources (similar energies, emittances, sizes, and currents)

Damping rings probably have most complex acc. physics issues



Rings use lots of wiggler to increase the synchrotron radiation!



Comparison with Operating Rings

- Compare random alignment and jitter 'tolerances'
  - Uncorrelated misalignments or jitter that would lead to equilibrium emittance, jitter equal to the beam size, or $\Delta\nu = 0.001$
  - These are not specs. on alignment but they are measures of the sensitivity
- Looking for significantly better alignment and stability than has been previously attained

	ALS	APS	SLS	ATF	NLC DR	TESLA DR
Energy	1.9	7	2.4	1.3	2	5
Circ	200	1000	288	140	300	17,000
$\gamma\varepsilon x$ [mm-mrad]	24	34	15	2.8	3	8
$\gamma\varepsilon y$ [nm-rad]	500	140	150	28	13	14
Yalign [μm]	135	74	99	87	38	13
Roll align [μr]	860	240	530	1475	400	45
Yjitter [nm]	850	280	337	320	93	91
$\Delta K/K$ [0.01%]	1.5	1.4	1.5	2.1	1.8	1.1

Wakefields and Tolerances

- The transverse wakefield is roughly 1000x smaller in TESLA than in JLC/NLC
  - Because of lower bunch charge, shorter bunches, and stronger focusing, in JLC/NLC the effect on the beam is not as large
  - The tolerances differ by ~50x in cavity alignment and 10x on quadrupole alignment
  - JLC/NLC wakefield is 25x larger than SLC but effect is 4x less
- JLC/NLC has approached the tolerances by systematically designing all components for beam-based alignment
  - Real lesson from the SLC diagnostics, diagnostics, diagnostics
  - JLC/NLC alignment tolerances are 20x tighter than SLC
    - Diagnostics are spec. to be 50x better
  - TESLA tolerances are comparable to SLC
    - Fewer diagnostics in the design than in SLC
- Will require excellent stability (both vibration and drift)

Differences between JLC/NLC and TESLA

- TESLA rf system based on superconducting cavities
  - \+ Lower peak rf power (easier klystrons and rf distribution)
  - \+ Better rf $\rightarrow$ beam efficiency
  - \+ Weaker wakefields (10 ~ 100x looser tolerances)
  - – Gradient limited to ~ 40 MV/m (SC material limit ~ 55 MV/m)
  - – Difficult beam generation and LLRF systems
  - – Tolerances are still very tight and now cavities and magnets are buried in cryostat

- JLC/NLC rf system is an extrapolation of the SLAC linac
  - \+ Subsystems are small extrapolations from existing accelerators
  - \+ Gradient limit is not clear: 70 MV/m possible - copper appears to hold ~ 150 MV/m
  - \+ Clear link to R&D for higher energy (multi-TeV) linear collider
  - – Tighter tolerances

International Milestones

- All three regions (ECFA, ACFA, and HEPAP) have endorsed a linear collider as the next major HEP facility
- Three regional LC steering groups have been formed and an international steering has been formed
  - **Goal is to make a technology choice in 2004**
- ICFA Technical Review Committee has completed review
  - NLC/JLC and TESLA are on track to demonstrate feasibility by 2004
  - Assuming rf feasibility, difficult to make a technology driven choice
- KEK presented JLC Roadmap at ACFA symposium
  - JLC design based on X-band with C-band as backup
- German Science Council reviewed the DESY project and gave conditional approval last summer
  - German government approved the FEL but urged DESY to work within international framework for the LC

How to Move Forward?

- Prof. Sugarawa's New Year's speech
  - "… Who and where shall we build the LC?
    One possibility, of course, is to build it in the most powerful country on earth, the United States.

    However, the U.S. particle physics community is divided, unfortunately; the east coast group extends eastward beyond the Atlantic Ocean and the west coast group extends westward beyond the Pacific Ocean. I believe the U.S. can take leadership only when the East moves westwards, the West moves eastwards, and they thus get unified. …"

- US Linear Collider Steering Group Accelerator Sub-committee
  Try to understand the relevant issues by comparing a warm and cold linear collider as constructed in the US
  - Gerry Dugan, Steve Holmes, David Finley, David Burke, Mike Harrison, Jay Marx, Hasan Padamsee, Tor Raubenheimer

Linear Collider Schedule

2004 Technology choice

2005 Formation of international design team and US bid to host

2006 Start of Project Engineering and Design (1 B$ for engineering design)

2009 Start of LC construction (6 year construction)

2013 Early physics at 250 ~ 350 GeV

2014 Construction project finished

2018 Energy upgrades start (Installation of 100 GeV during each 3 month shutdown)

2023 Operation at 1 TeV

Optimistic schedule!

Why X-Band: My opinion

- Why X-band instead of superconducting?
  - Superconducting has loose tolerances and stability however these are not *necessary* nor are they *necessarily easier* to achieve in the cryostats
  - Entering new regime with massive superconducting facility—will limiting effects be found that cannot be seen in the TTF?
  - Many sub-systems are very different from anything demonstrated

- Why X-band instead of lower rf frequencies?
  - The technology exists and the tolerances are attainable
    - Present prototypes are better than tolerances
    - Directly use knowledge from SLC and other large-scale prototypes
  - Support higher gradients: 70 ~ 100 MV/m for cheaper collider and higher energy reach
  - X-band provides essential knowledge-base for continued progress in e+/e– colliders at higher gradients and possibly higher rf frequencies

Summary

- RF feasibility demonstrations are planned for X-band and SC this year
- Coordinated work on luminosity performance is starting
  - Unlike rf systems, hard to demonstrate in a ‘small’ test facility
  - Few complained about the energy of the operating SLC, Tevatron or HERA although these issues dominated the design process
  - A number people have been concerned about these luminosities!
- US LC SG AS is preparing an evaluation of NC and SC at a US site
  - Designs for 500 GeV with an upgrade path to 1 TeV
- Will make an international technology choice in mid-2004
- The linear collider is a twenty to thirty year commitment