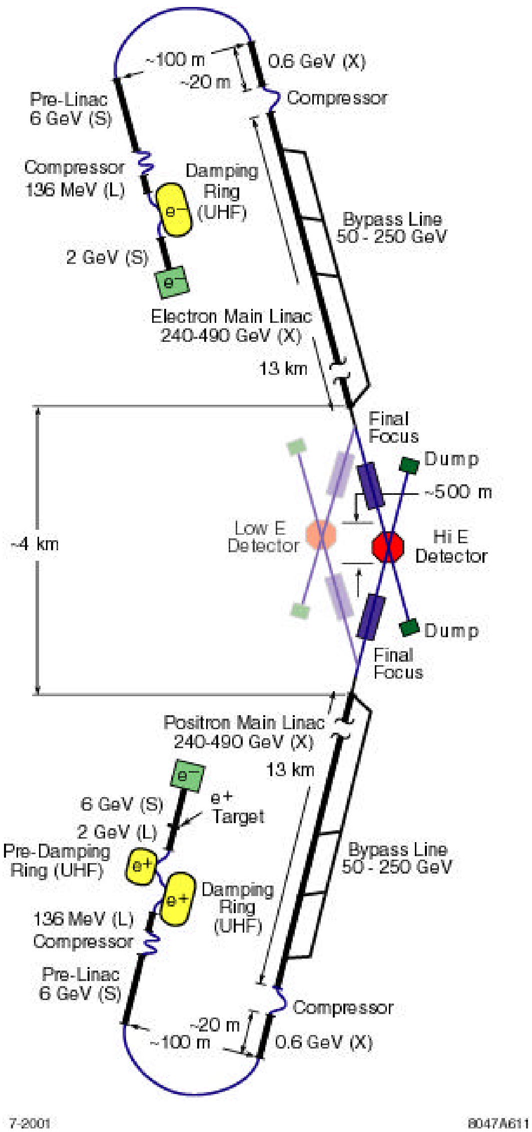


NLC Design Status

ANL
January 23, 2002

Tor Raubenheimer

SLAC

Outline

- Two issues for LC: energy and luminosity
- RF systems
  - Modulators, klystrons, cavities and test facilities
- Luminosity issues
  - Parameters
  - Damping rings and sources
  - Main linac dynamics and alignment
  - Beam delivery systems
  - IP issues

- Either TESLA or NLC could be built
  - different risks and different connections to the future

Linear Collider RF Systems

- The RF systems consist of 4 primary components:

Modulators:
line ac → pulsed dc for klystrons
TESLA distributes pulse dc (12 kV) in long 2.8km 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 / 3.1 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

Accelerator Structures:
→ power to beam, prevent dipole mode instabilities

X-Band RF System

NLCTA RF system (ZDR, 1996):

- Conventional PFN modulator (500 kV, 500 A, 1.5 μs)
- 50 MW / 1.5μs solenoid-focused klystrons
- SLED-II pulse compression
- DDS structures work at gradients up to 45 MV/m

→ Tested, could be used to build a 500 GeV collider

Improvements to reduce cost and improve performance:

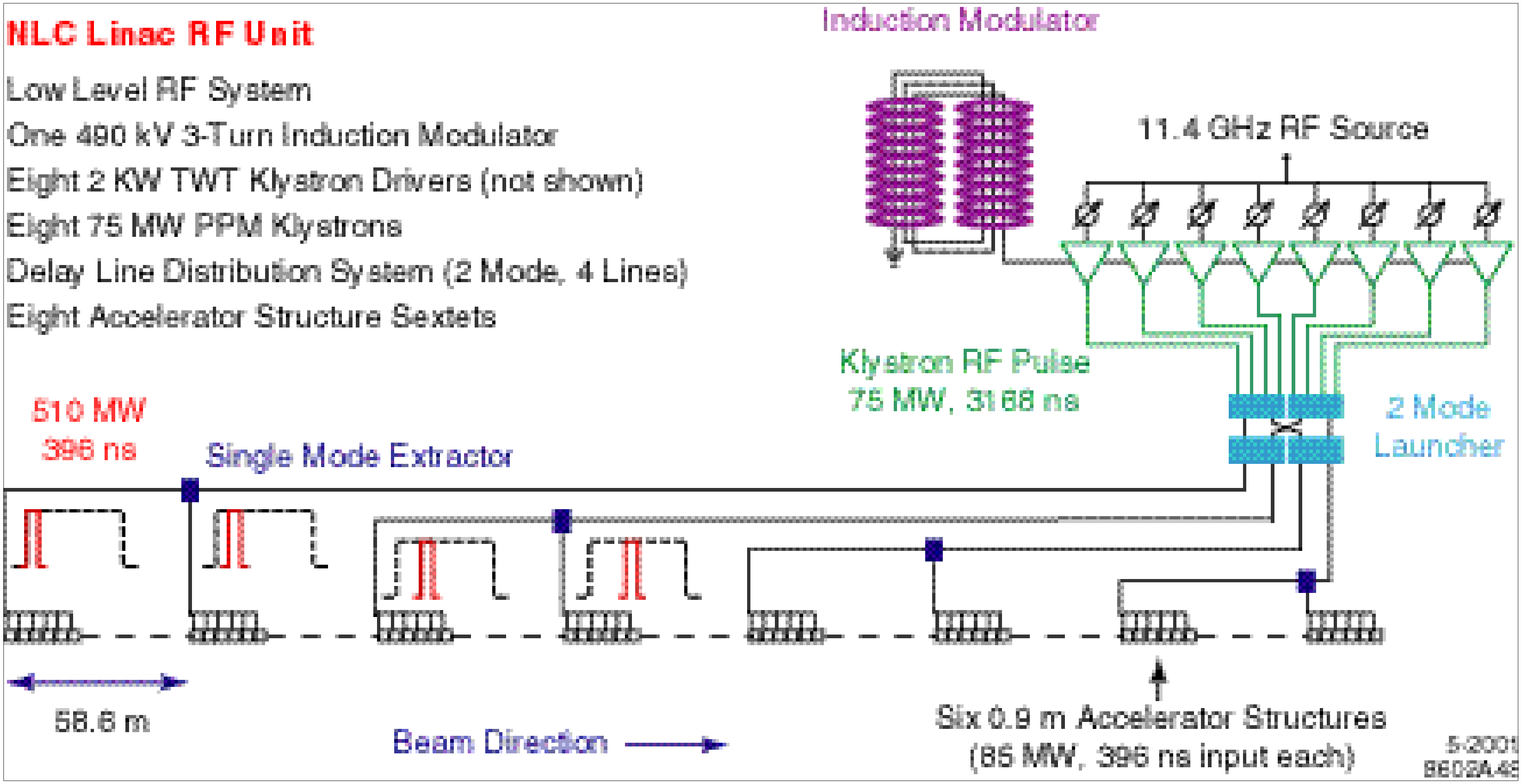
- Solid state modulator (500 kV, 2000 A, 3 μs)
- 75 MW / 3μs PPM-focused klystrons
- DLDS pulse compression
- RDDS structures - 70 MV/m

→ Aimed to optimize performance and cost at 1 TeV

X-Band RF Unit

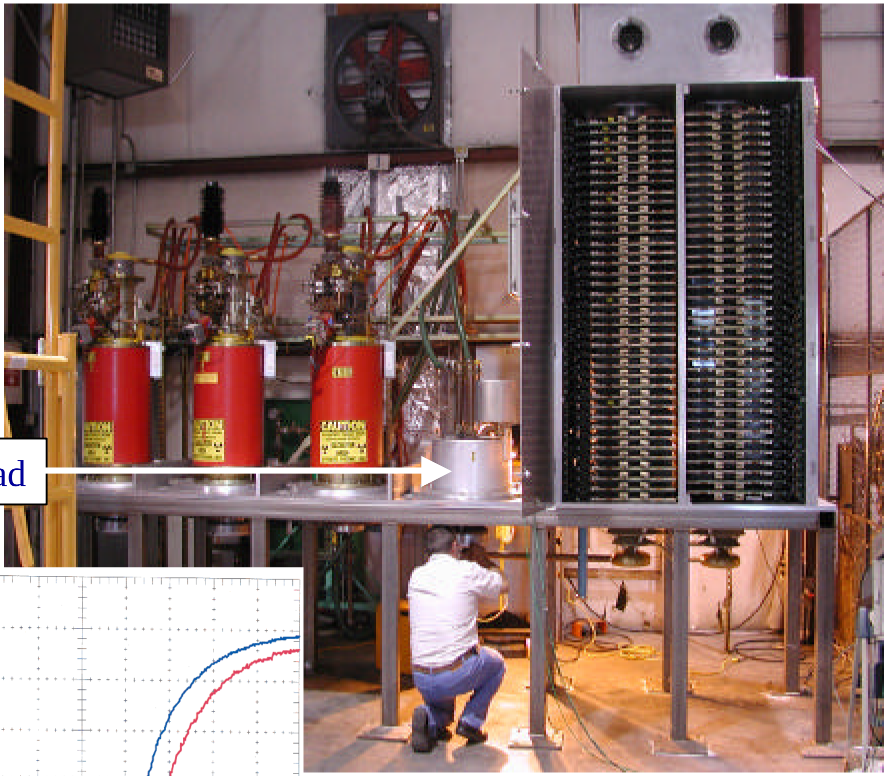
Two-Mode '8-Pack'

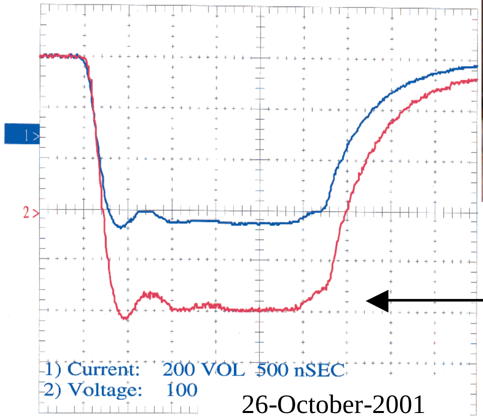
(NLC version - JLC is similar)



Modulators

- Both NLC and TESLA have modulator designs based on solid state IGBT's
- Switch MW's of power and deliver lots of energy
  - NLC: 500 kV, 2000 A, 3.1 μs
  - TESLA: 12 kV, 1600 A, 1.7 ms
- TESLA has designed tested a few versions at TTF – energy storage and efficiency issues
- NLC prototype solid state modulator testing started in October





NLC Klystrons

- Over 14 X-band klystrons built and operated
  - XL4’s are work horse for NLCTA and other test stands (many tubes with 10 ~ 20,000 hours)
- Periodic Permanent Magnet (PPM) for increased efficiency

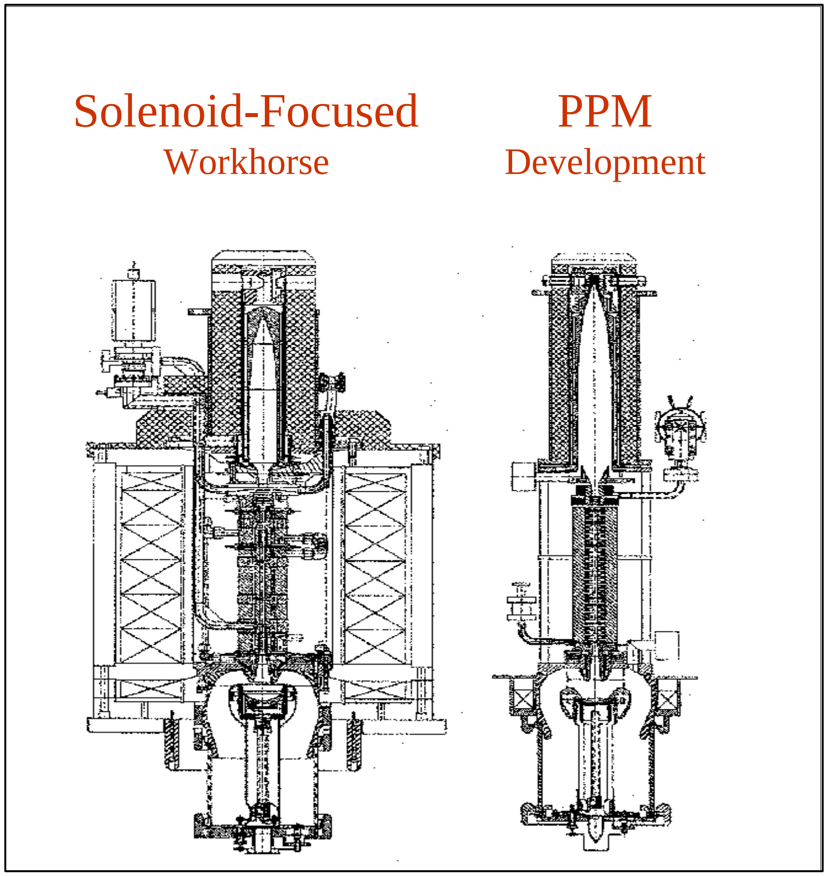
Present goal: 75 MW with 3 μs pulse width at 120 Hz or greater

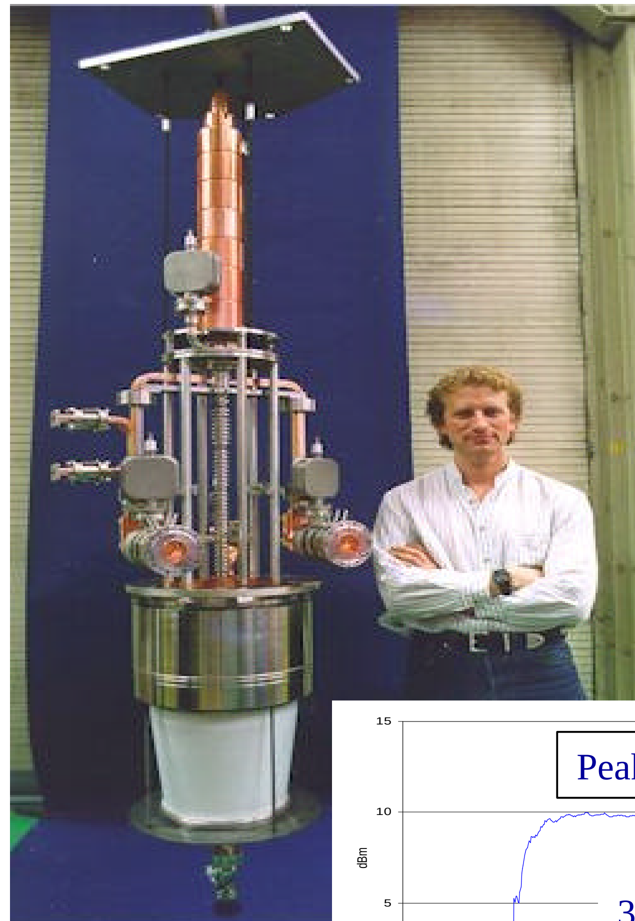
XP3 results look good

Recent success at KEK with 75 MW and 1.5 μs looks good

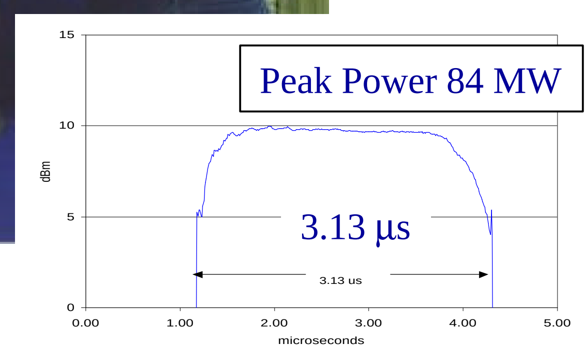
	Focusing	Peak Power	Pulse length	Rep. rate
XL4	**Solenoidal**	**50 MW**	**1.5 us**	**120 Hz**
10 tubes @ 10,000 hrs.		50 MW	1.5 us	120 Hz
		75 MW	1.5 us	120 Hz
		50 MW	2.4 us	120 Hz
X5011	**PPM**	**50 MW**	**1.5 us**	**60 Hz**
1 tube (1996)		60 MW	1.5 us	60 Hz
		50 MW	2.4 us	60 Hz
XP1	**PPM**	**75 MW**	**1.5 us**	**No cooling**
1 tube (2000)		75 MW	3.1 us	
		90 MW	0.5 us	
XP3	**PPM**	**75 MW**	**3.0 us**	**120 Hz**
Diode test (2001)				

Permanent Magnet Focused (PPM) Klystrons





achieved
>70 MW
@ 3 µs



Next Generation Tube Designed for Manufacturability will be tested this year

Energy: RF Distribution

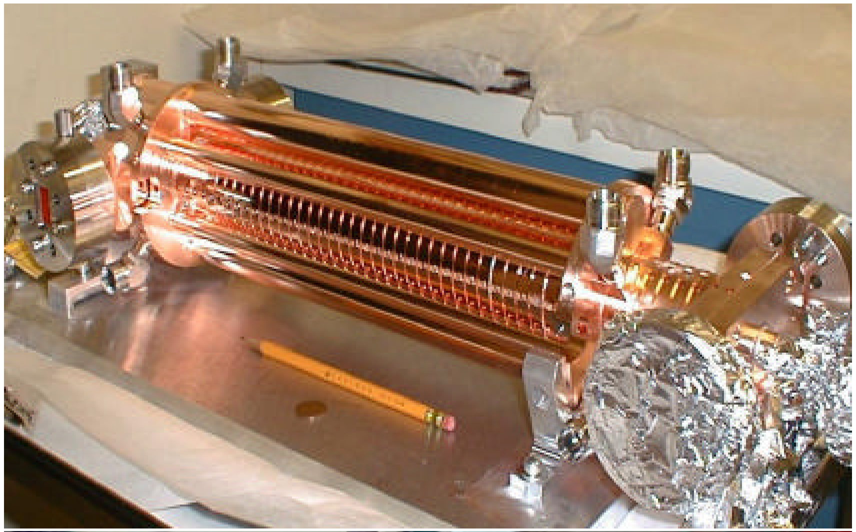
- Delay Line Distribution System (DLDS)
  - Complicated rf components to exchange modes and direct power
  - Massive vacuum system
  - Completely passive rf switching
  - Next step: validate rf power handling (600 MW in 400 ns)
  - Systems tests in 2002 and 2003

- SLED-II – previous pulse compression system
  - Less efficient than DLDS (65% instead of 85%)
  - Many similar power handling issues
  - Maximum power tested thus far is 500 MW at 150 ns and 400 MW at 240 ns
  - Operating on NLCTA since 1996

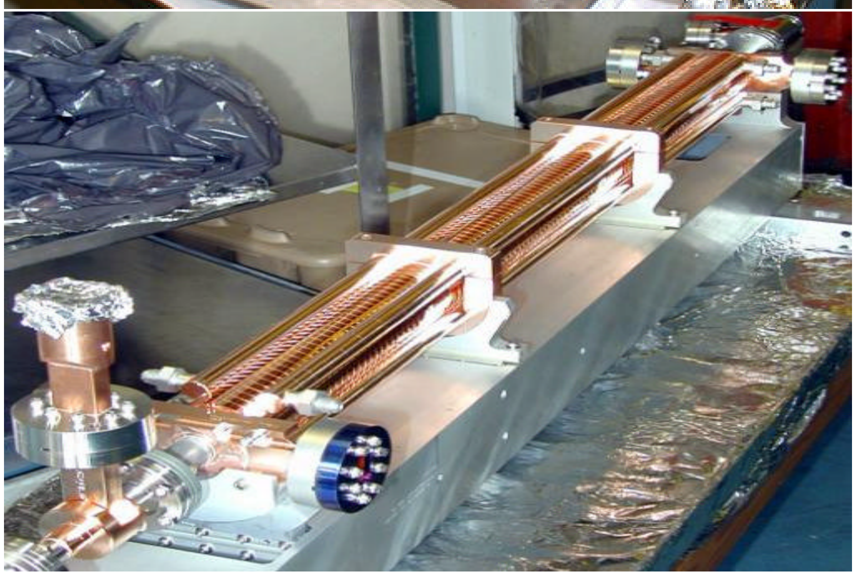
NC Accelerator Structures

- Not near gradient limits for copper
  - Single cell cavities hold gradients of ~ 200 MV/m
  - ‘Short’ structures processed rapidly to >100 MV/m
- Built many 1.3-m ~ 1.8-m structures
  - Meet fabrication tolerances
  - Studied wakefield damping extensively – damping sufficient although not at desired values due to trivial errors, solutions in-hand
  - Stable operation limited to 40 ~ 45 MV/m
- Processing model – increase voltage until breakdown
  - Small arcs clean surface / large arcs damage surface
  - Difference between the two is how much energy is deposited → low vg
  - Some ‘damage’ is acceptable however need to extrapolate out 10~20 years
  - Other models predict constant damage – inconsistent with single cell data

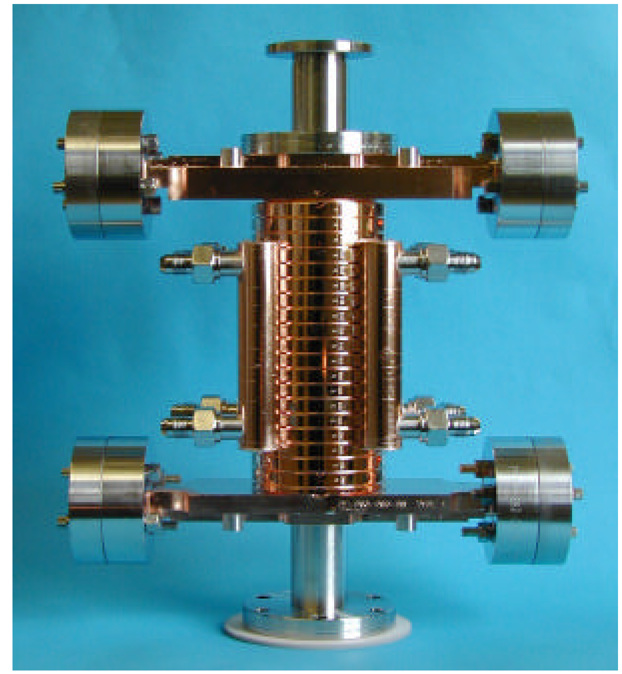
Low Group Velocity Test Structures



DS2S
52 cells DS2



105 cm test
5% to 1% v_g



20 cm test
5% to 4% v_g

Rapid processing to >70 MV/m

DS2S 1500 hrs @ 50-70 MV/m

Others 500 hrs @ 65-75 MV/m

Two new traveling wave structures operating at 70 ~ 80 MV/m

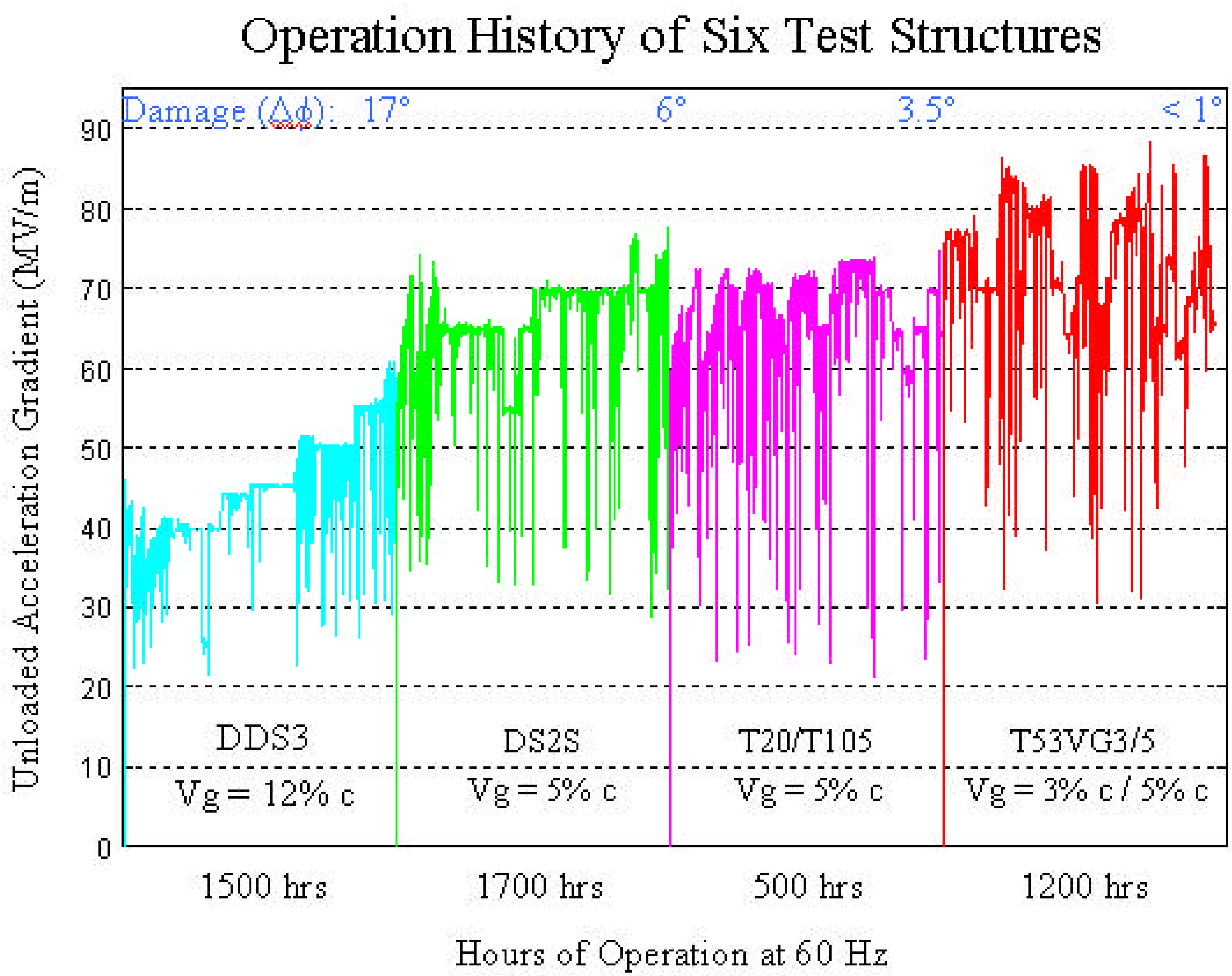
Gradient Issues

- Low group velocity structures rapidly process to ~70 MV/m

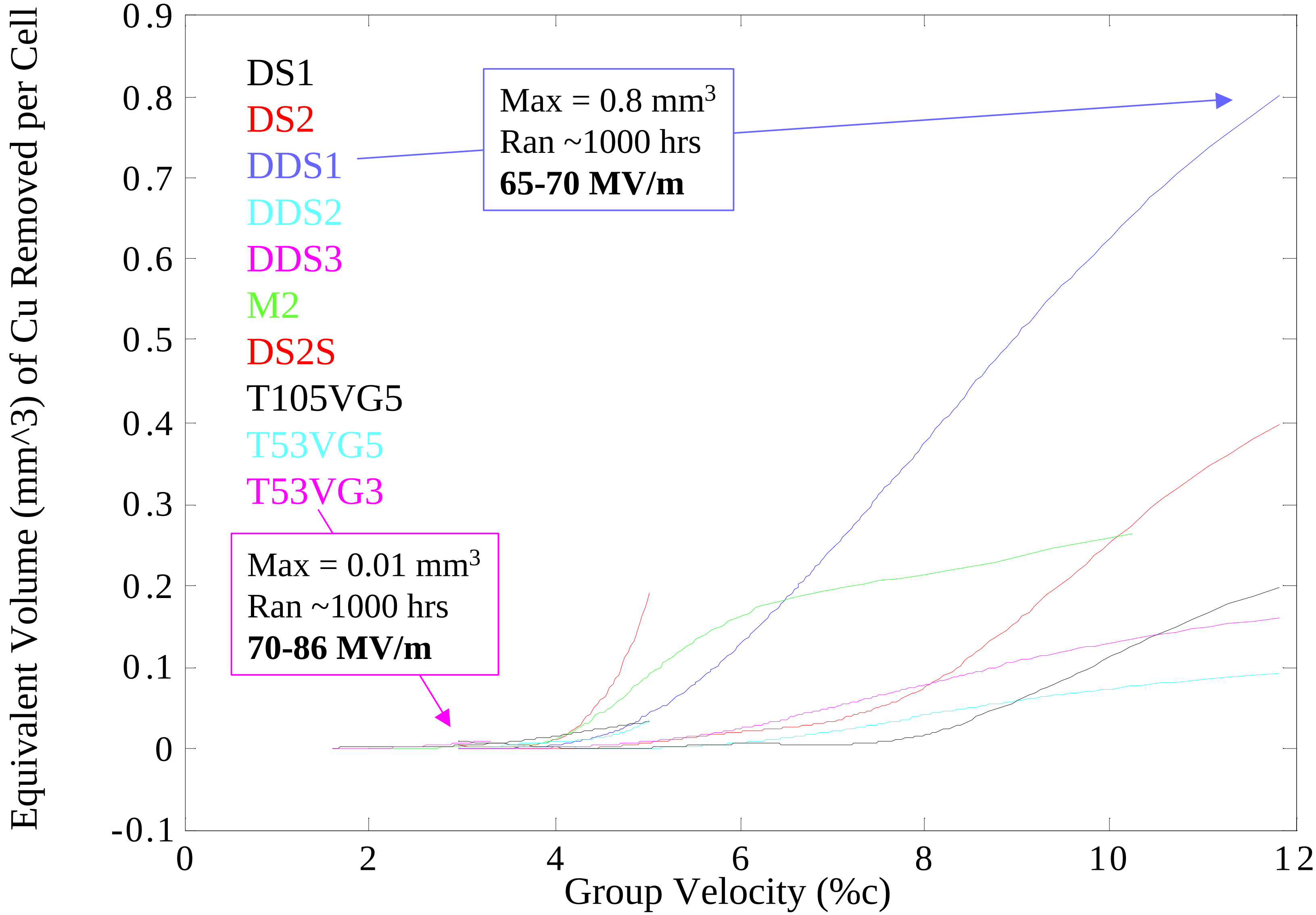
- Small damage during initial processing seen with beam

- Minimal damage during subsequent operation

- Breakdown rate is few per hour, i.e. few per 200,000 pulses

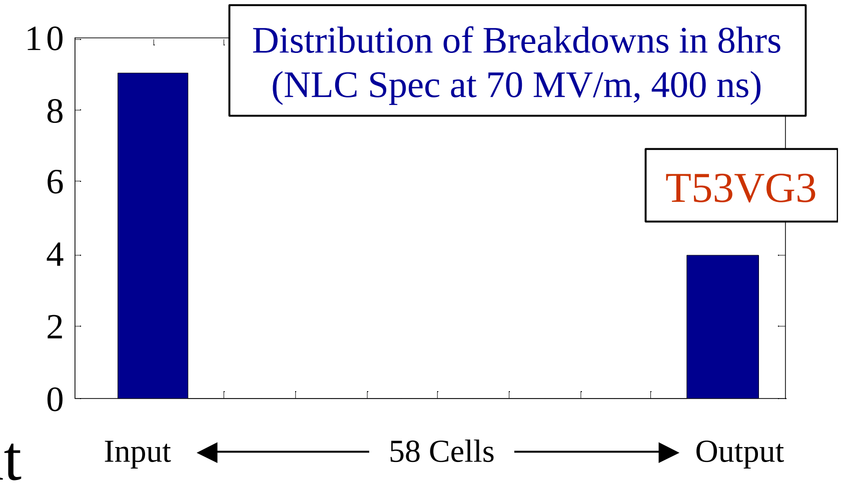


Structure Damage



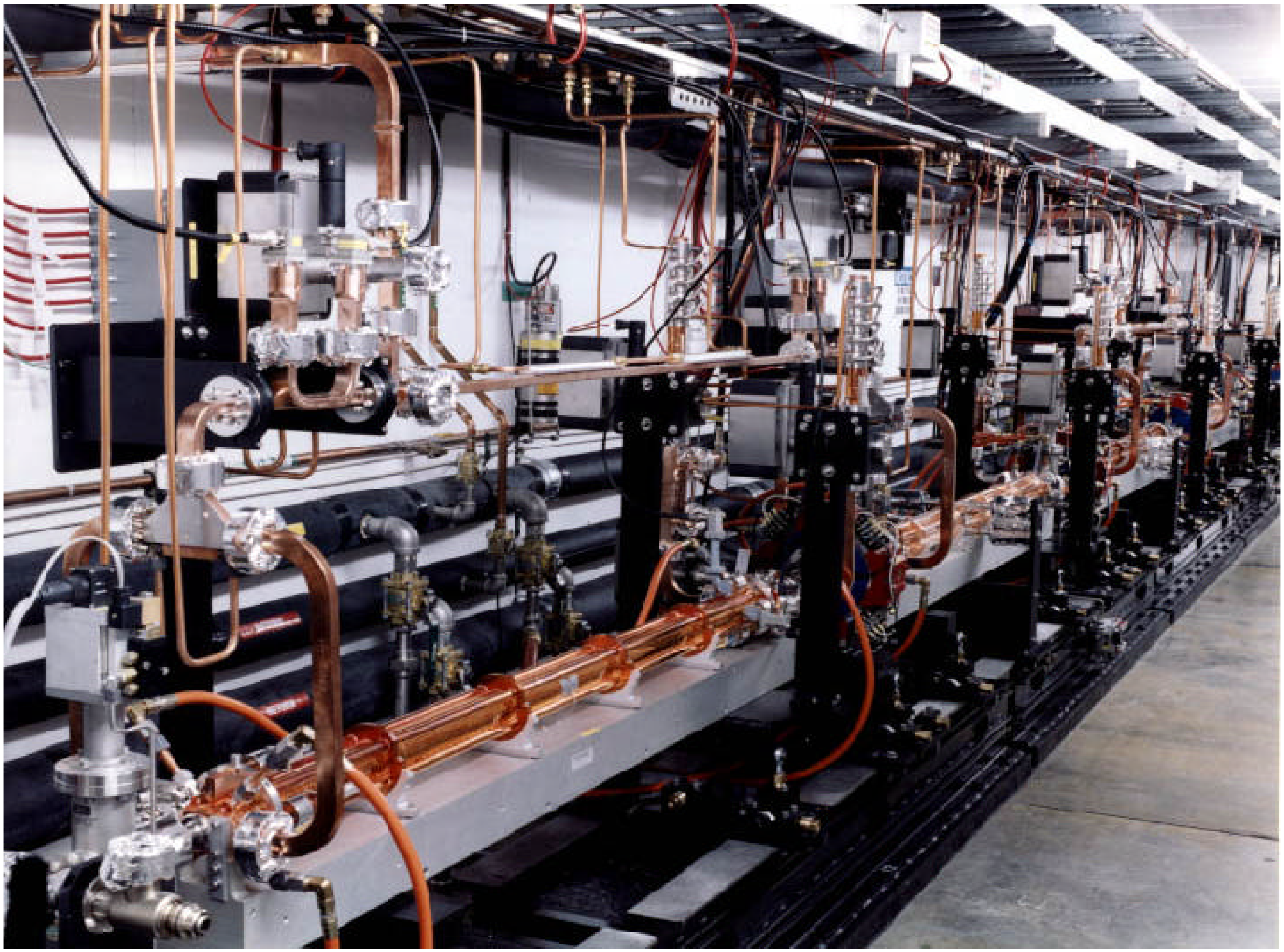
NLC Accelerator Structures

- Built many test structures to study gradient limitation
  - Much better performance with low vg than original NLC design
  - Peak gradients of 80 to 90 MV/m and operate at 65 to 75 MV/m
  - Trip rates look OK
  - Damage looks OK



- Next step: combine NLC-style wakefield control with high gradient
  - Demonstrated single and multi-bunch wakefield control in 1.8-m structures
  - Will build 'NLC' style 90 cm structure with single bunch wakefield control end of this year
  - Will test NLC structures with both single and multi-bunch wakefield control by the end of 2002

NLC Test Accelerator



Operated since 1996

5000 hrs just this year

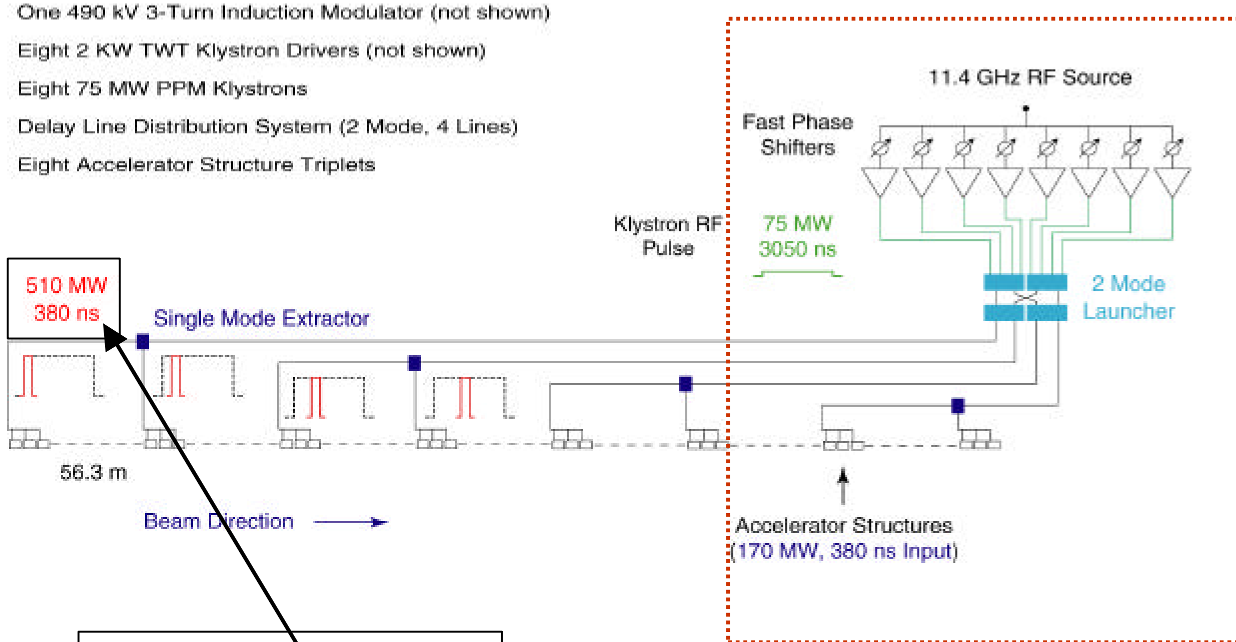
Essentially NLC-500 rf system from 1996:

- Dual 50MW klystrons
- SLED-II
- 1.8 m long structures

NLC RF System Tests

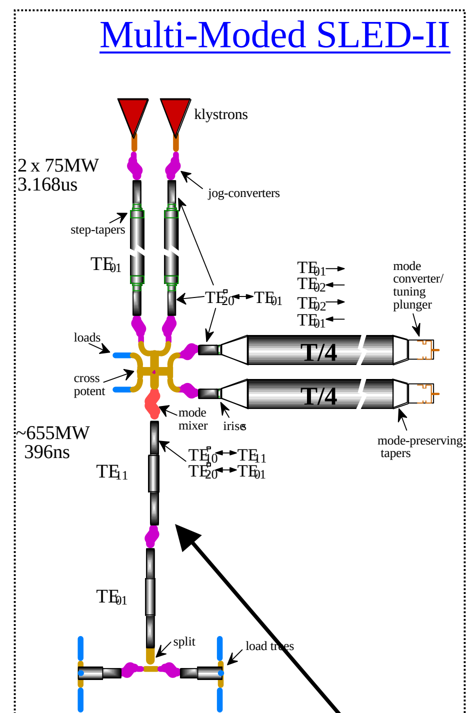
NLC Linac RF Unit

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



NLC "Single Feed"
(5.4 m of Accelerator)

"Single-Feed"
Intermediate Step
Fall 2002



650 MW in 400 ns

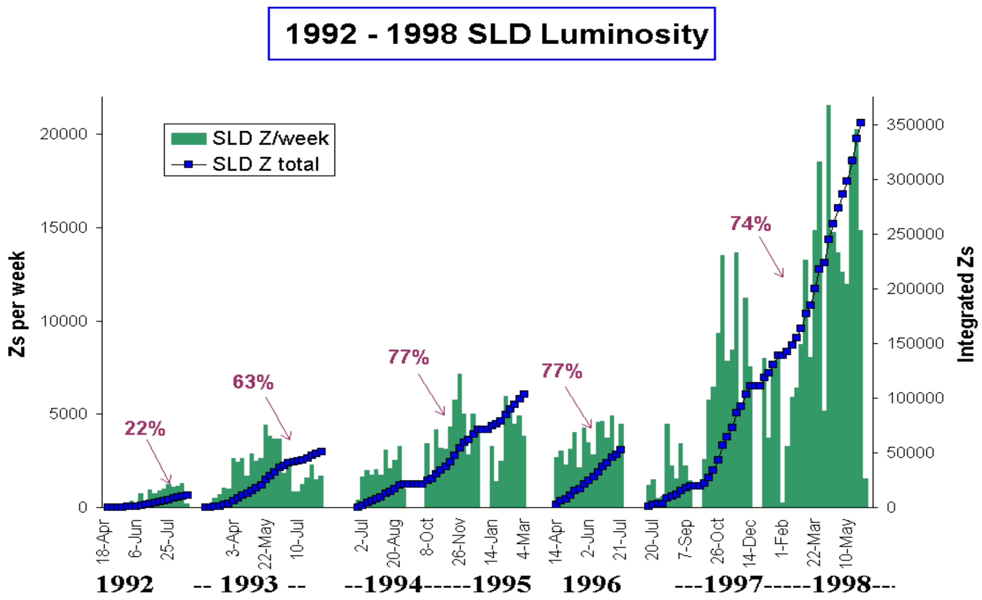
Full "8-Pack"
NLCTA end of 2003
Modulator; klystrons;
¼ DLDS; 12 structures

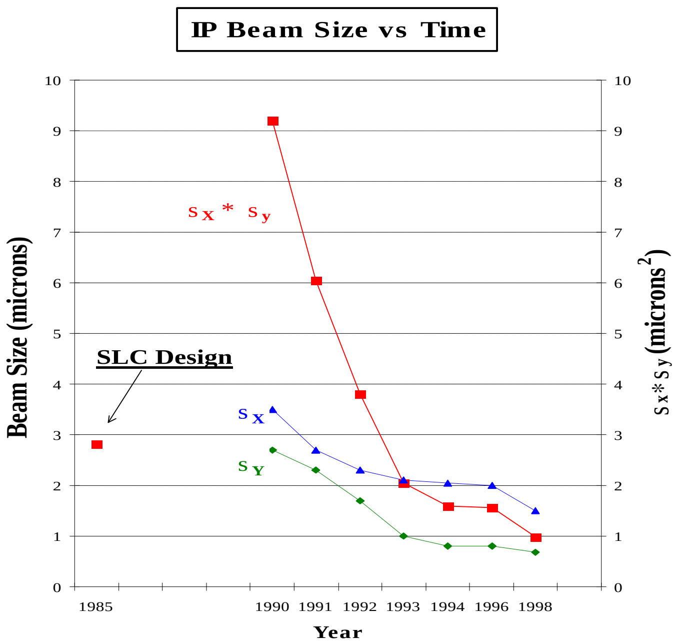
2001 JLC/NLC Parameters

	Stage 1		Stage 2	
CMS Energy (GeV)	500		1000	
Site	US	Japan	US	Japan
Luminosity (10^{33})	**20**	**25**	**30**	**25**
Repetition Rate (Hz)	120	150	120	100
Bunch Charge (10^{10})	**0.75**		**0.75**	
Bunches/RF Pulse	192		192	
Bunch Separation (ns)	1.4		1.4	
Eff. Gradient (MV/m)	**48.5**		**48.5**	
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 2		300 / 2	
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	360		360	
ge$_y$ at IP (10^{-8} m-rad)	**4**		**4**	
β_x / β_y at IP (mm)	8 / 0.11		13 / 0.11	
s$_x$ / s$_y$ at IP (nm)	**243 / 3.0**		**219 / 2.3**	
q$_x$ / q$_y$ at IP (nm)	**32 / 28**		**17 / 20**	
σ_z at IP (um)	110		110	
Υ_{ave}	0.14		0.29	
Pinch Enhancement	1.51		1.47	
Beamstrahlung δB (%)	5.4		8.9	
Photons per e+/e-	1.3		1.3	
Two Linac Length (km)	12.6		25.8	

- High current parameters
- Additional parameters with slightly lower charge 0.65×10^{10} and smaller beta functions for similar luminosity
- Low energy parameters also exist for operation at the Z, W, low-mass Higgs, and top

Luminosity: Building on the SLC





New Territory in Accelerator Design and Operation

- Extensive feedback & online modeling
- Correction techniques expanded from first-order (trajectory) to include second-order (emittance), and from hands-on by operators to fully automated control

"It's the diagnostics, stupid"

"The damping rings are the source of all evil"

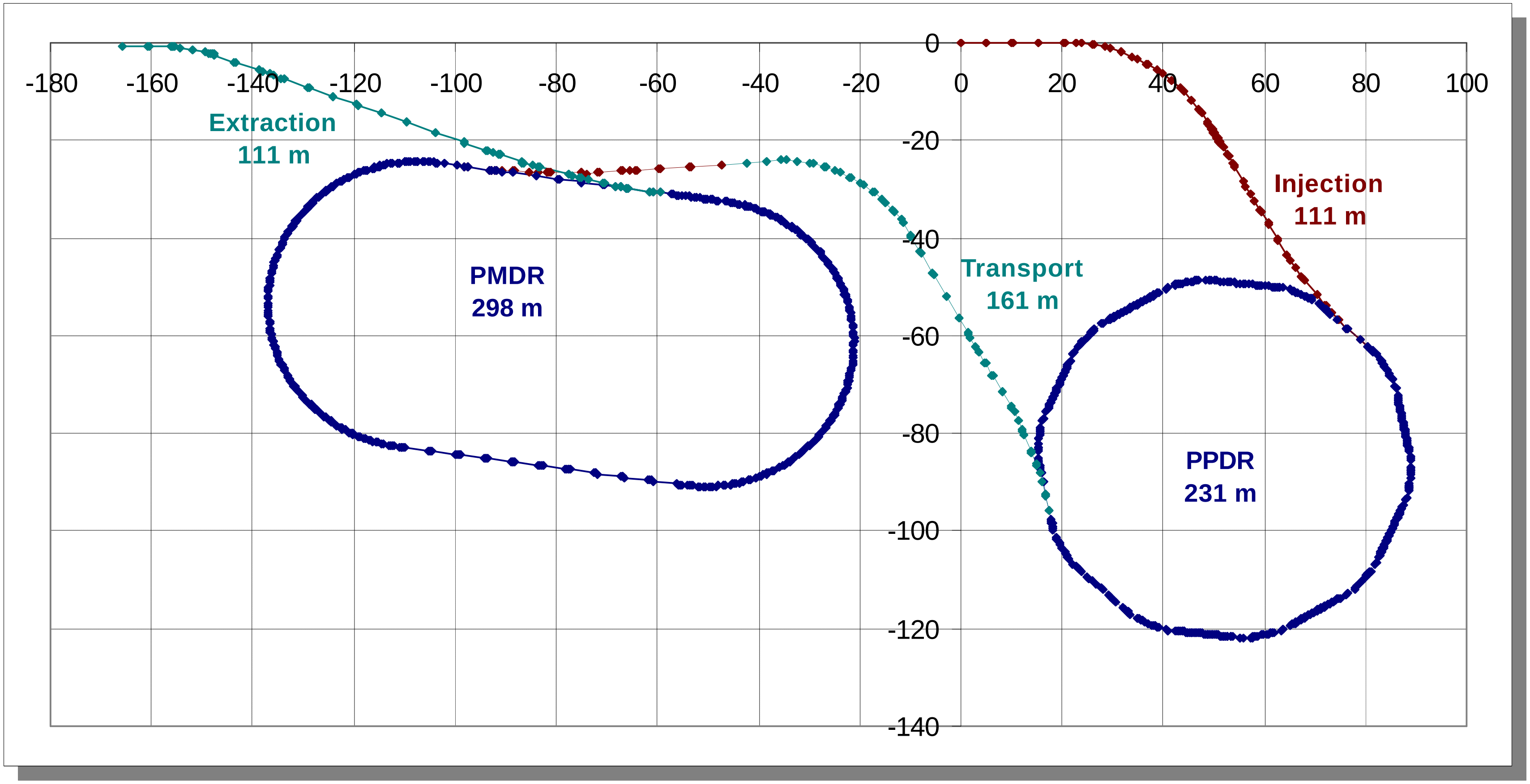
Electron and Positron Sources

- Both are based on ‘conventional’ sources used at the SLC
- Polarized electron source had limitation due to ‘Surface Charge Limit’
  - Electrons would be trapped at the surface generating a potential barrier for further electrons
  - Problem has been solved by varying the doping with depth
  - Laser system is not commercially available but should be possible
- SLC positron target was damaged at end of the SLC run
  - Diagnostics at LANL and modeling at LLNL
  - Design with 3 interleaved targets for robust design
  - Also looking at TESLA-style undulator-based system
    - Need a number of modifications to make system robust

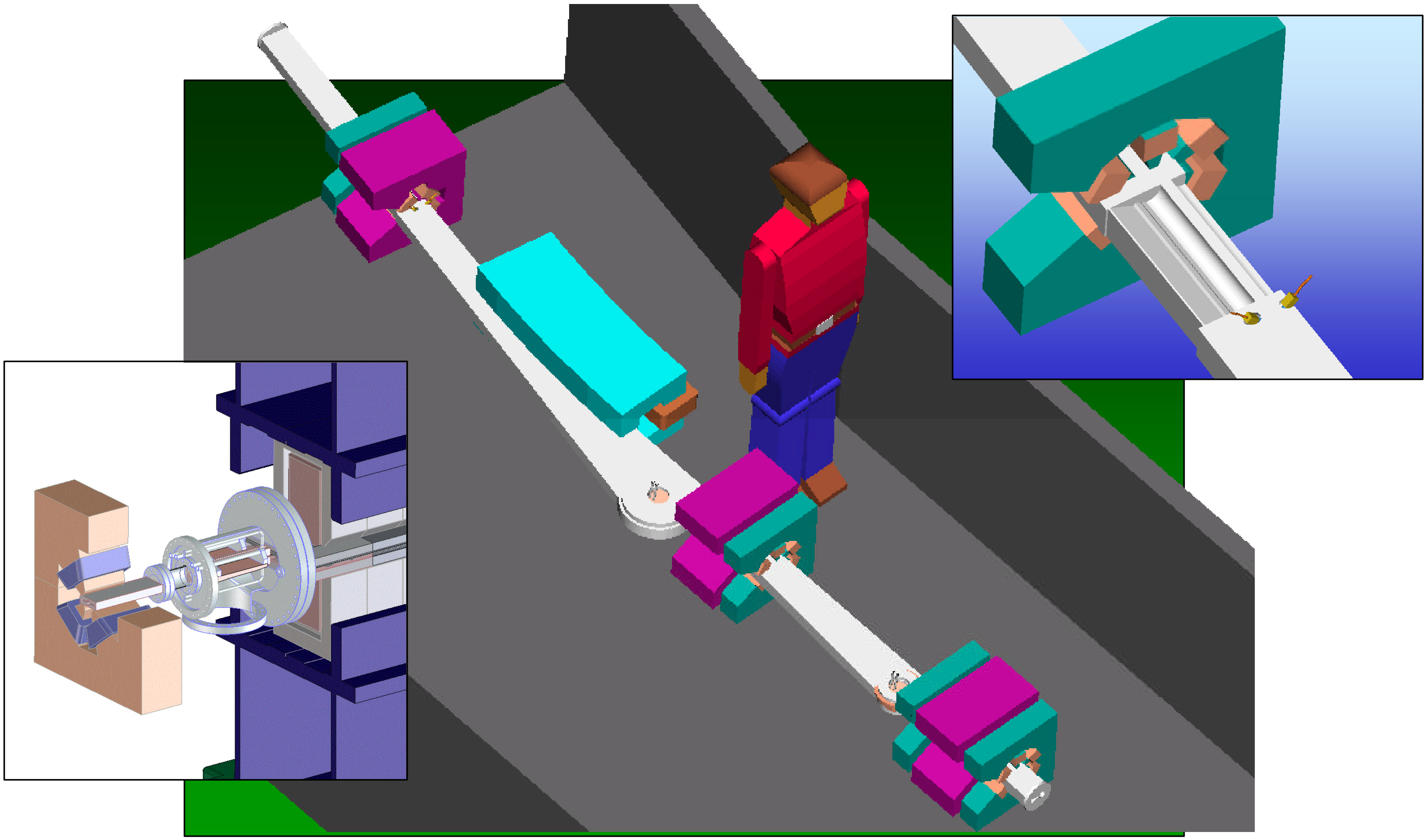
Damping Rings

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

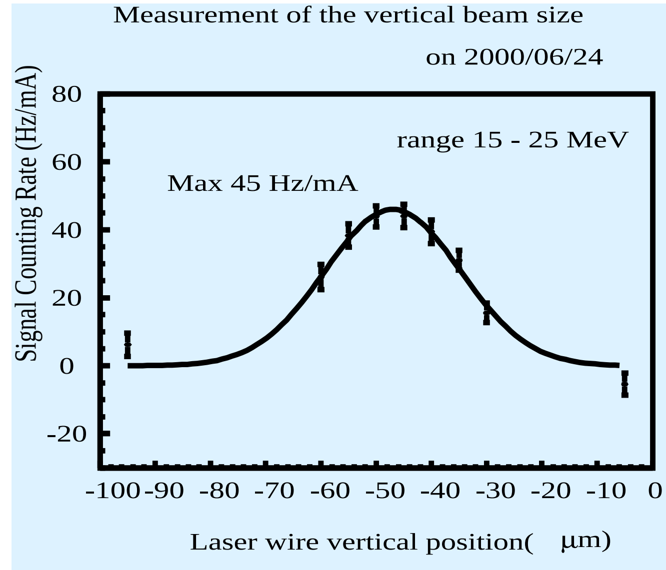


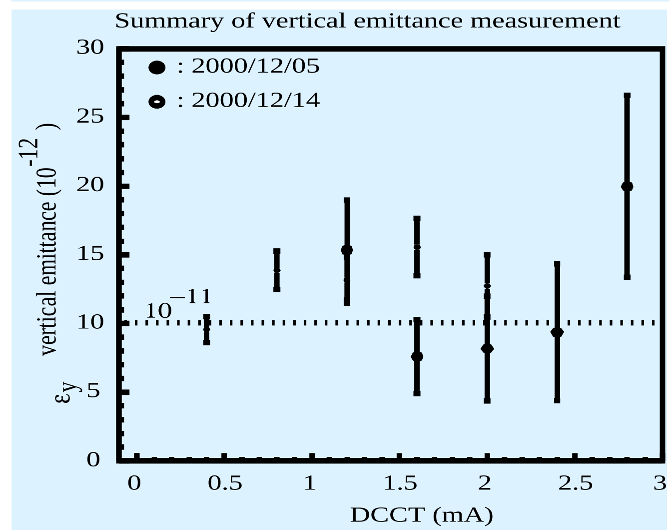
Main Damping Ring
Engineering Model



ATF Damping Ring at KEK

Vertical emittance 3.5×10^{-8} measured with laser wire (~2 x NLC spec)





Linac Dynamics

- Two separate issues: Beam BreakUp (BBU) and ‘static’ alignment or emittance dilutions
  - BBU quasi-exponential amplification of incoming trajectory errors
    - Well understood and well simulated!
    - Multi-bunch BBU seen in 60’s in SLAC linac
    - Single bunch BBU solved in SLC in mid-80’s
    - Need to measure/model wakefields
  - Quasi-static emittance dilutions
    - Cavity alignment
    - Magnet alignment
    - Rf deflections
    - Stray fields
    - Use beam-based alignment!
    - Techniques developed and tested at SLC, FFTB, ASSET, and elsewhere!

BBU: Wakefield Summary

- Wakefields have been measured in the TTF and the ASSET facility at SLAC using beam
  - Both wakefields are larger than design although sufficient
    - NLC errors were due to known construction errors
    - TESLA cavity errors were due to calculation errors
  - Both cases are not ‘final’ prototype cavities
    - Final prototypes available in 2003 for NLC and 2004? For TESLA
  - Devil is in the details!

- NLC aims to measure ‘final’ cavity prototype in 1.5 yrs
  - Must develop high gradient structure with low group velocity and wakefield control
- TESLA will choose between 2x9 superstructure and present single cavity design
  - 2x7 superstructure to be tested next year and 2x9 to follow

Beam-Based Alignment (e Tuning)

- To preserve emittance must correct **net** effect of individual dilution sources

NLC

- ‘Local’ correction - directly correct dilution sources
  - Beam-based alignment – tested SLC; FFTB; other beam lines
  - Most robust solution / least sensitive to energy or strength errors
- ‘Quasi-Local’ correction - correct dilution effects over short distance, i.e. betatron wavelength
  - Dispersion-Free steering – tested in SLC; LEP; other rings
  - Based on ‘measurements’ of dilution / sensitive to systematics
- ‘Global’ correction - tune emittance using direct ε diagnostics
  - Directly corrects desired quantity / sensitive to phase advance – tested SLC

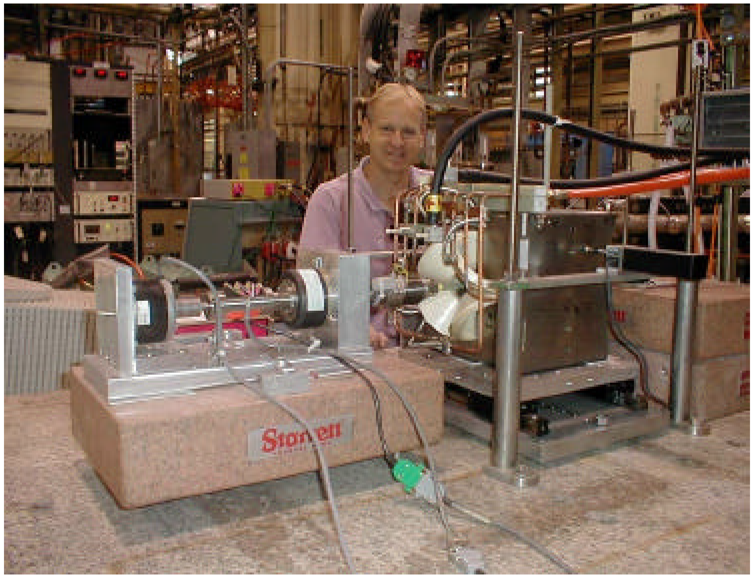
TESLA

Alignment Tolerances

- Alignment tolerances in NLC/JLC are very tight!
  - 1 - 10 μm in the main linacs and similar in the final focus
- Lesson from SLC: diagnostics and control
  - Want 300 nm Beam Position Monitor resolution
    - FFTB/SLC FF striplines have 1 μm resolution
    - FFTB RF cavity BPM had 40 nm resolution
  - Want beam size resolution of 300 nm
    - SLC laser wire had between 500 and 230 nm resolution
    - FFTB 'Shintake' BSM had 40 nm resolution
  - Want magnet movers with 50 nm step size
    - FFTB magnet movers have 300 nm step sizes
- With sufficient diagnostics and controls - accelerator becomes big feedback loop but easy to diagonalize
- Stability very important for convergence!

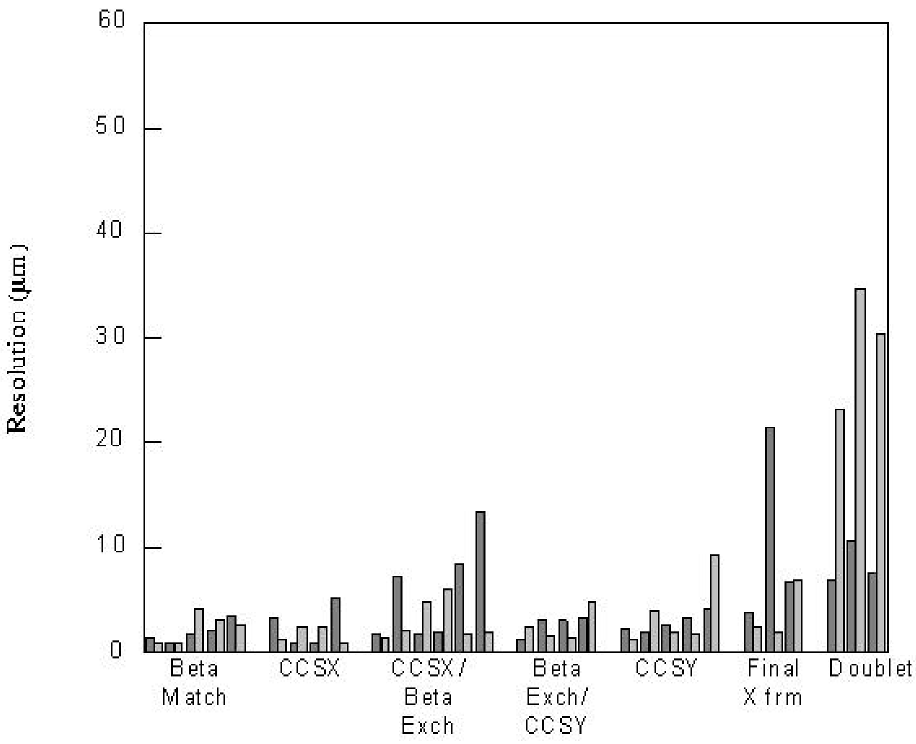
Quadrupole Alignment

- Quadrupoles must be aligned using beam derived information
- Tolerance corresponds to roughly 100 μm ‘dispersion’ error (dispersion is not exact in linac with varying energy spread)
  - With 1 μm BPM resolution, 100 μm dispersion not so bad!
- Desire very local correction (align every quadrupole perfectly) with a procedure that does not interrupt luminosity
  - Measuring quadrupole center shifts at SLAC and FNAL
  - Find <1μm motion in EM quads but much larger in PM quads
  - Investigating alternate routes (DF steering, ε-bumps, ballistic corr.)
  - Thinking about beam tests



FFTB Quadrupole Alignment

- Used quadrupole shunting technique
  - Fit residuals ranged from 2 µm to 30 µm at the end of the beam line
    - FFTB optics poorly designed for beam-based alignment
    - Ran out of BPMs to measure deflected trajectory!
  - Dispersion measurements show errors in 1st two regions < 7 µm after alignment
    - Confirms technique
  - NLC designed for BBA with better diagnostics and smoother optics
    - Would expect a factor of 2 ~ 3 improvement
  - TESLA has poorer ratio of tolerance to diagnostic res.

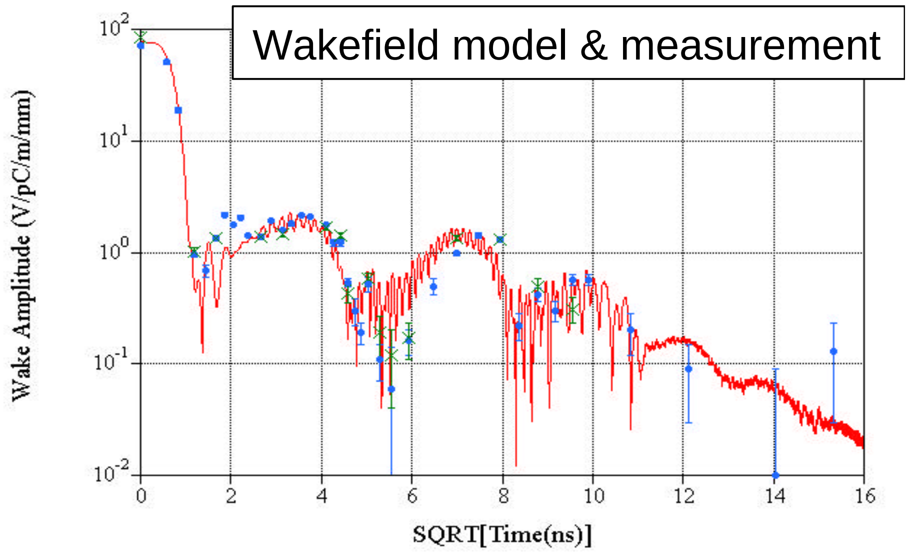


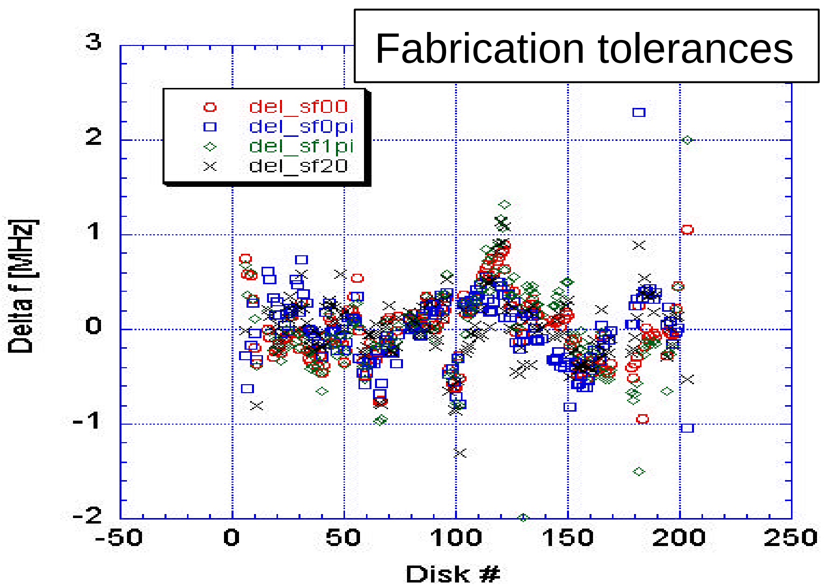
Structure Design Issues

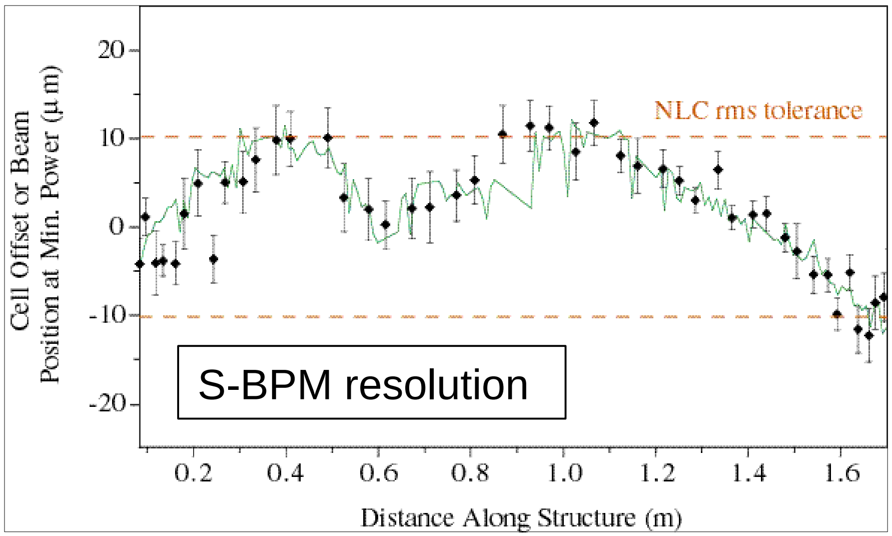
Precision wakefield measurements agree well with model prediction

Fabrication achieved frequency errors 0.5 MHz rms (tolerance 3 MHz)

Structure BPM achieved < 1 µm centroid resolution (tol. 20 µm)







Rf Cavity Alignment

- NLC structures (cavities) must be aligned to beam within 10 μm rms for 20% Δε
  - Every structure has two rf-BPMs with better than 2 μm accuracy
  - Short-range wakefields depend on average of structure offset
  - Average position of the 6 structures on an rf girder and move girder end-points with remotely controlled movers

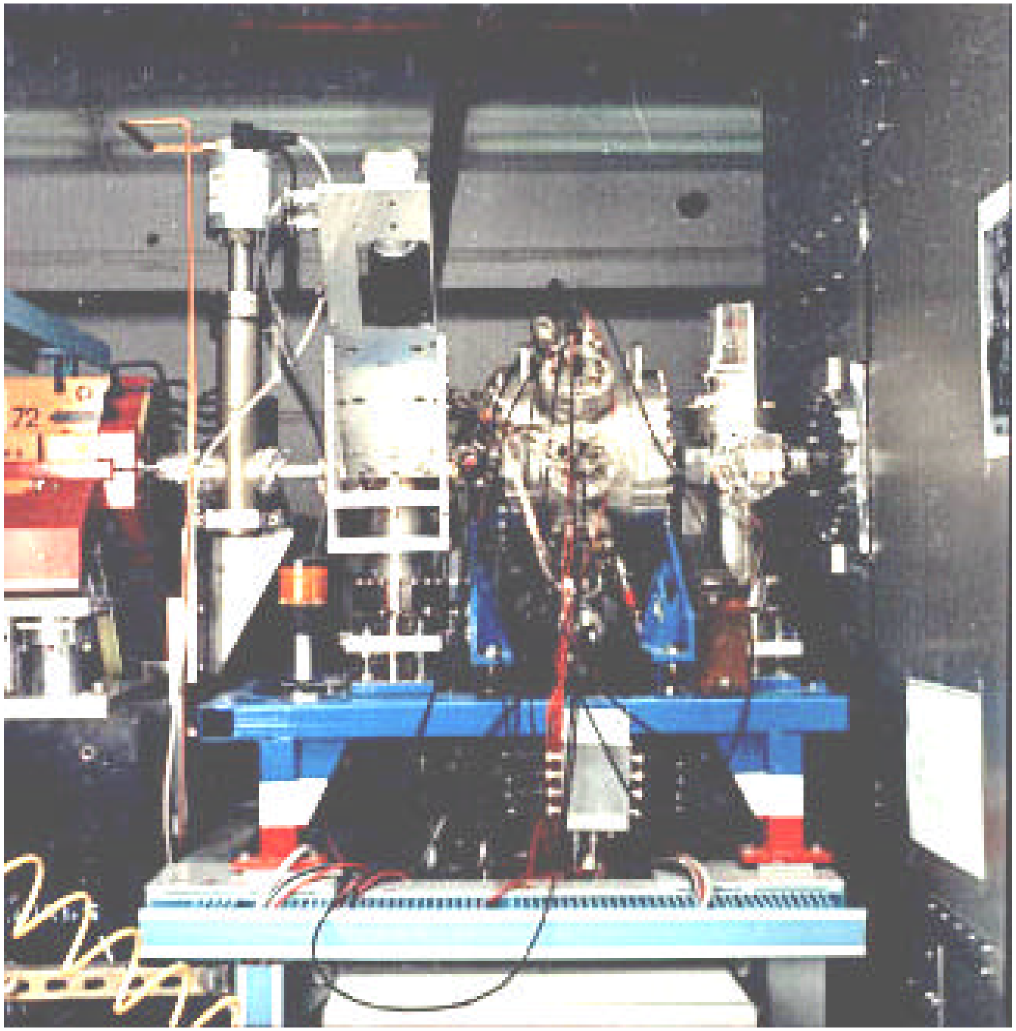
- TESLA cavities must be aligned with 500 μm rms for 15% Δε
  - Achieved +/- 250 μm alignment within cryostat
  - But effects add → tolerance for 12 cavities in cryostat ~ 140 μm
  - Effect is worst at $\frac{1}{4}\lambda_\beta$ = 150 m → tolerance for cryostats ~ 45 μm
  - Either add read-backs on HOM dampers and steer beam to center of cavities or use global emittance bumps like those used in SLC to cancel dilutions
  - RF deflections imposes 100 μrad tolerance on cavities for 5% Δε

Beam Delivery Systems

- TESLA BDS based on conventional lattice while NLC and CLIC are based on new Pantaleo FFS
- Alignment and jitter tolerances are similar (factor of 2)
  - New FFS appears to have better performance but NLC and CLIC demand more from systems so tolerances are 1.5~2x tighter
- Low repetition rate makes ground motion a larger problem
  - Fast intra-train feedback at TESLA designed to handle fast beam jitter however does not yet treat spot size variation
  - No plans to test system; possible sensitivity to IR backgrounds
- Collimation system solved for NLC and solution can be applied to TESLA

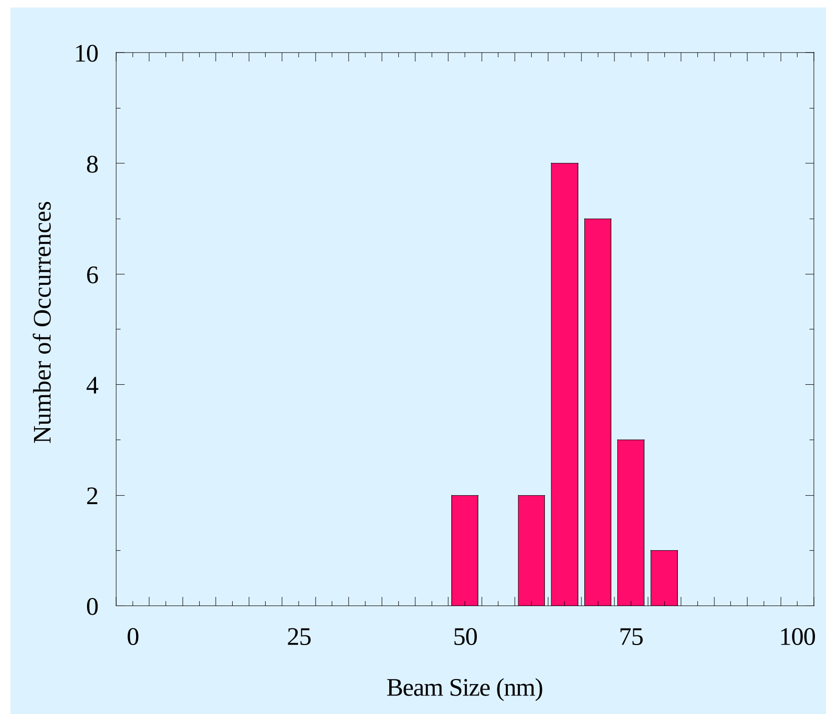
Final Focus Test Beam at SLAC

FFTB IP



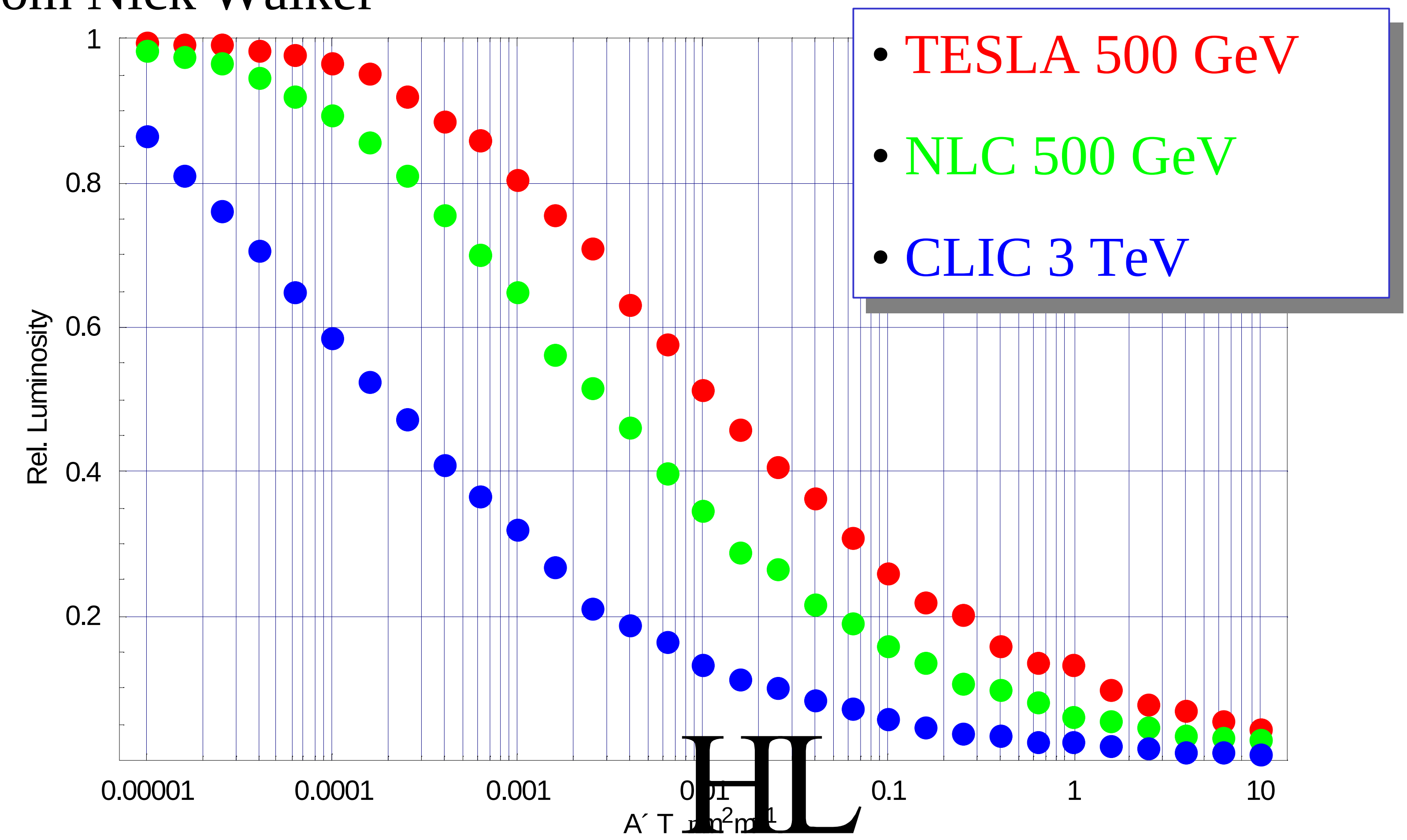
FFTB measured vertical beam size of 60-70 nm at IP with laser interferometer

Demonstrated precise diagnostics!



Beam Delivery Systems

From Nick Walker



With FNAL or CA deep tunnel NLC FFS can operate for ~1year between BBA

Beam-Beam Issues

- High disruption → single bunch kink instability
  - Sensitive to IP position and angle offsets (IP feedback)
  - Sensitive to position correlations along the bunch, i.e. $\Delta\varepsilon$
  - Fractional luminosity decrease is much larger for correlated errors such as those from the linac or bunch compressor

Simulation by R. Brinkmann including IP feedback tuning

	Uncorr. $\Delta\varepsilon$	Corr. $\Delta\varepsilon$
L_{design} ($\Delta\varepsilon = 50\%$)	$3.4\text{x}10^{34}$	
L_0 ($\Delta\varepsilon = 0\%$ i.e. from DR)	$4.1\text{x}10^{34}$	$4.1\text{x}10^{34}$
L_{sim} ($\Delta\varepsilon = 10\%$)	$3.9\text{x}10^{34}$	$3.2\text{x}10^{34}$
L_{sim} ($\Delta\varepsilon = 20\%$)	$3.7\text{x}10^{34}$	$2.7\text{x}10^{34}$

  - Effect can be reduced by decreasing bunch length but this increases beamstrahlung energy spread
  - Smaller fractional effect for large emittance dilutions and smaller disruption – initial calcs. suggest smaller problem in NLC design

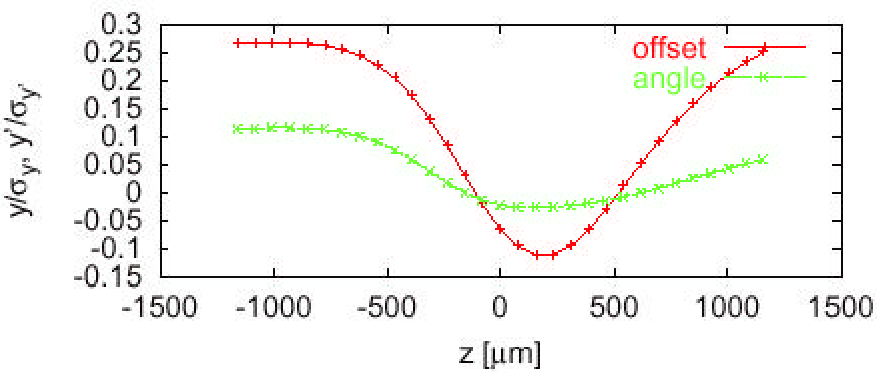
Disruption Values

	TESLA		NLC		CLIC
Energy	500		500		3000
N	2.00E+10		7.50E+09		4.00E+09
DR emitx		8.00E-06		3.00E-06	
DR emity		2.00E-08		2.00E-08	
IP emitx	1.00E-05		3.60E-06		6.80E-07
IP emity	3.00E-08		3.50E-08		2.00E-08
betax	15		10		8
betay	0.4		0.1		0.15
sigmax	5.54E-07	4.95E-07	2.71E-07	2.48E-07	4.30E-08
sigmay	4.95E-09	4.04E-09	2.67E-09	2.02E-09	1.01E-09
sigmaz	3.00E-04		1.10E-04		3.00E-05
Dy	**24.82**	**34.02**	**12.89**	**18.71**	**5.14**
L0	1.64E+34	2.24E+34	1.41E+34	2.04E+34	6.67E+34
Approx Hd	1.74E+00	1.81E+00	1.39E+00	1.47E+00	1.91E+00
Approx Lum	2.85E+34	4.06E+34	1.95E+34	2.99E+34	1.27E+35

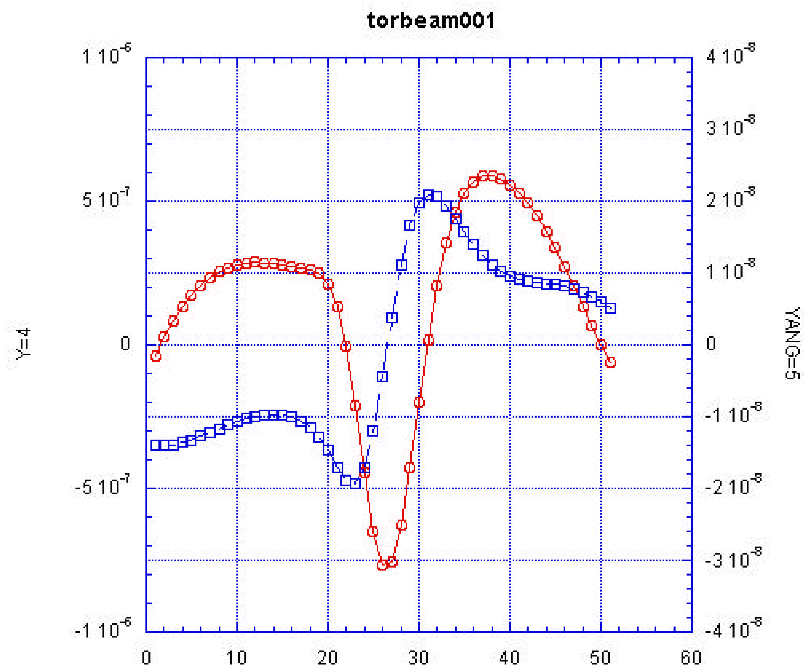
Correlated Emittance Dilutions

- Usually estimate luminosity based on increase in projected spot sizes
- Correlated emittance growth arises from bunch compressors and linacs

TESLA



NLC



Gaussian Beam Simulations

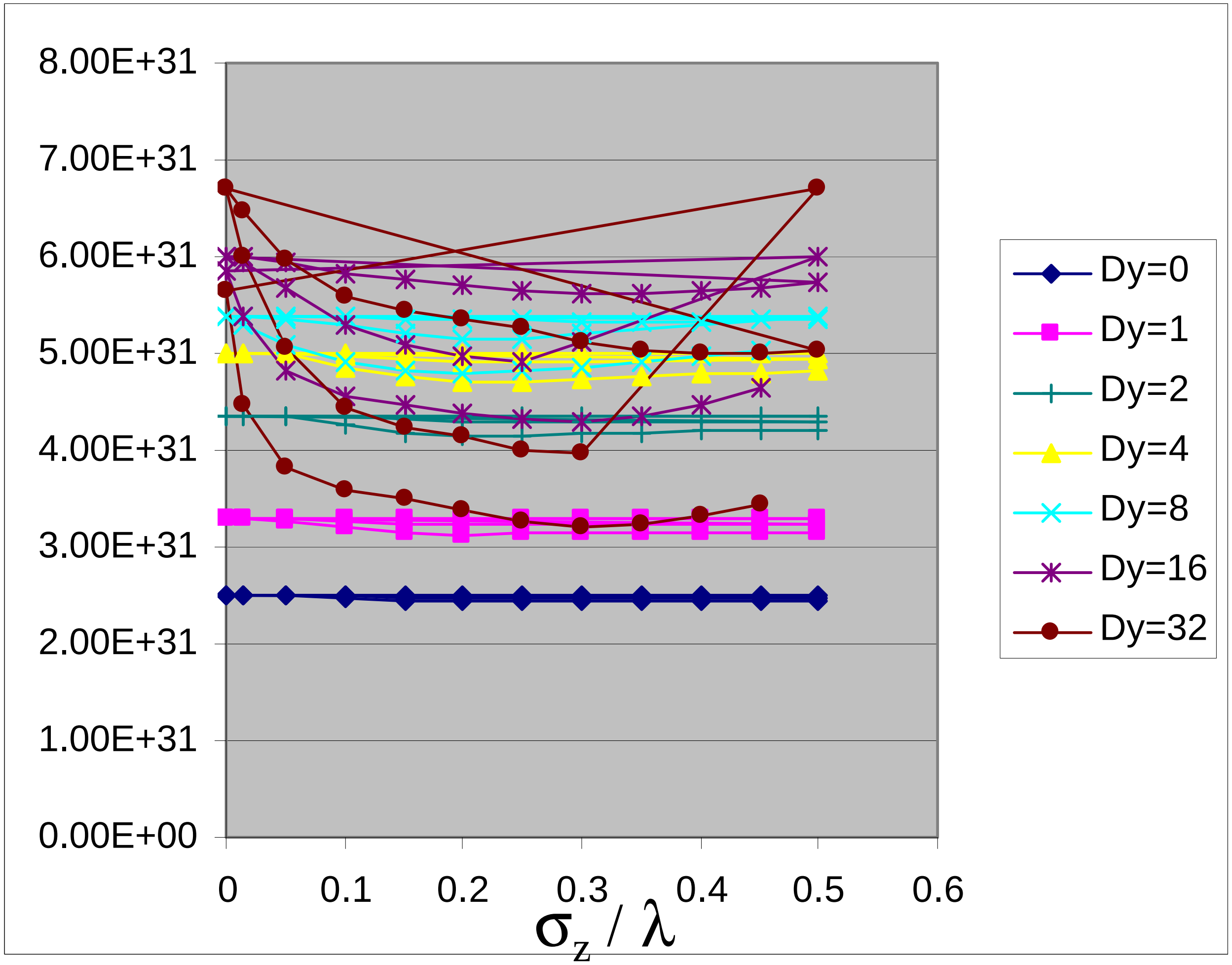
From Daniel Schulte

Sinusoidal offset versus σ_z / λ

Each D_y has 3 curves for $y = 0.1, 0.3, 0.5\ \sigma_y$

Note increase in luminosity with D_y due to pinch

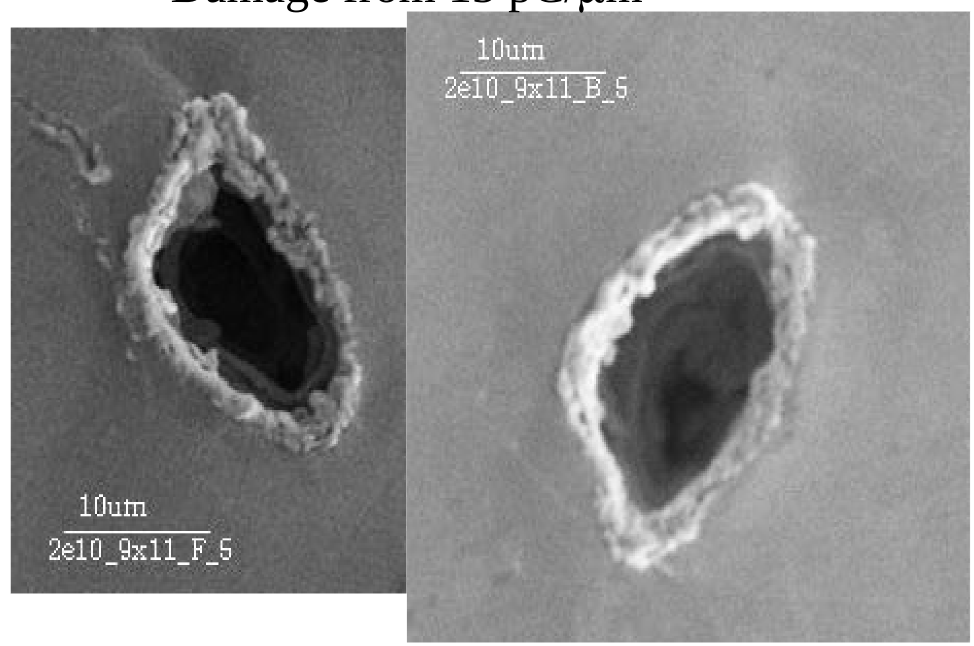
Effect reduces pinch enhancement



Machine Protection Issues

- Single bunches will likely damage any material at the end of the linac or in the beam delivery
  - Complicated turn-on process to prevent damage
  - Complicated MPS system with diagnostics on many components
    - Anything that can change from pulse-to-pulse

Damage from 13 pC/μm^2



  - Some impact on operation not yet fully quantified
  - Problems are similar for TESLA and NLC!

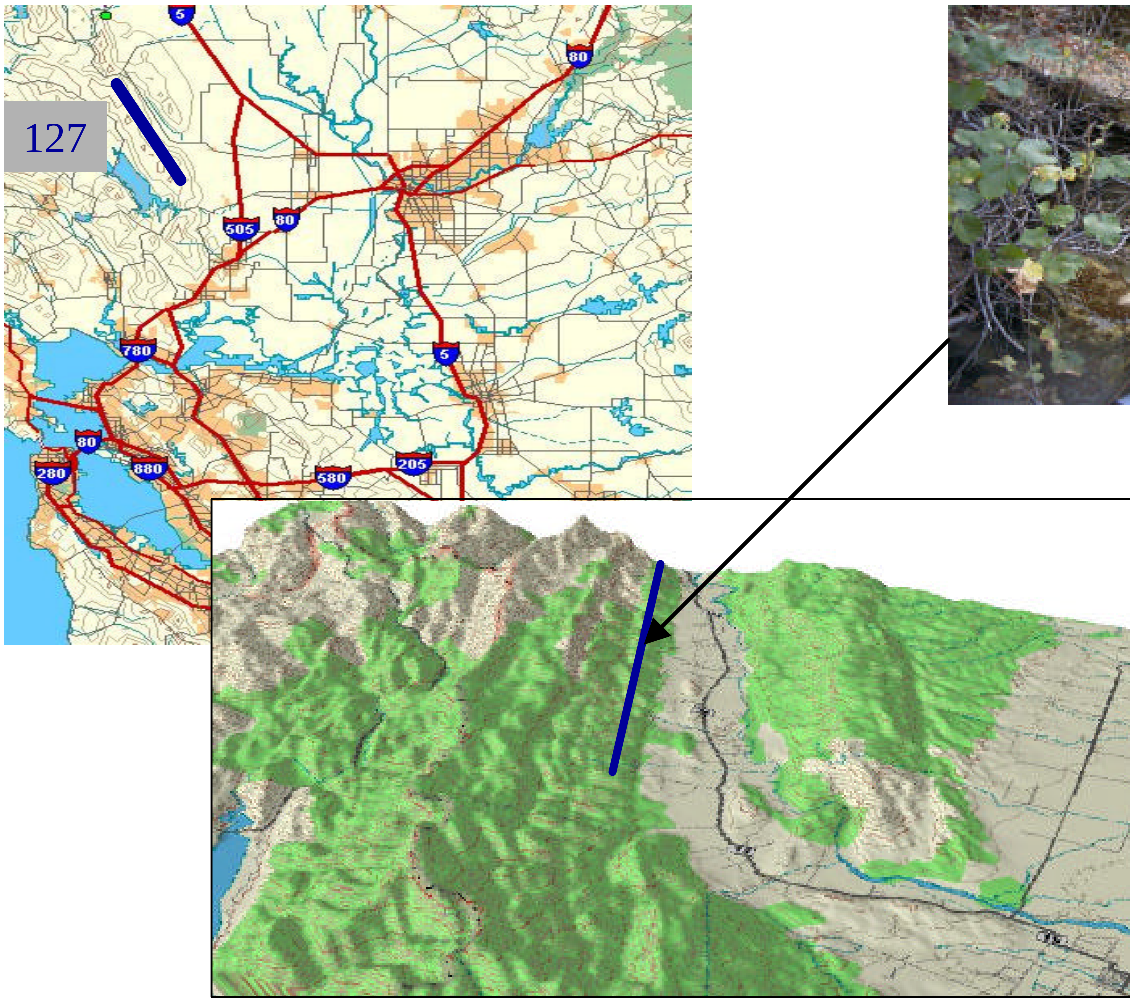
Reliability Issues

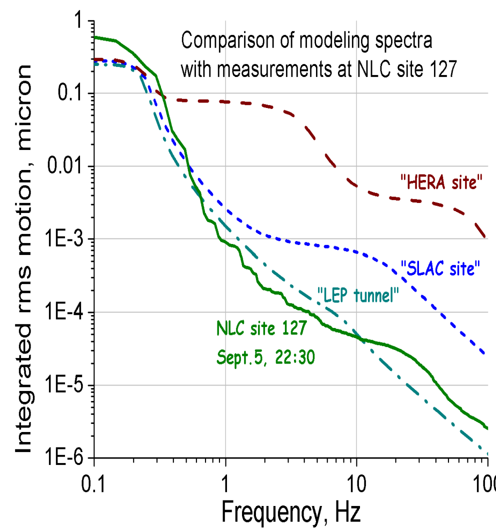
- Essential to understand!
  - Significant limitation in SLC operation
    - Would take 3 ~ 4 times the length of each down time to recover luminosity!
- New LC are being designed to avoid known problems
  - Multiple (redundant) power supplies
  - Overhead in klystron / modulator populations
  - Redundant electrical / cooling systems
  - Big questions regarding TESLA single tunnel with accesses/10 days
    - Radiation levels have only been checked at 17 MV/m (turned off 1 cavity)
    - Operation model based on 40,000 hr klystron lifetime – only operated for ~2000 hrs at 25~40% power and 1 Hz
    - Modulator cables; temp stability; low level rf electronics
- Must qualify reliability of all components, especially those in the tunnel!

Operational impacts

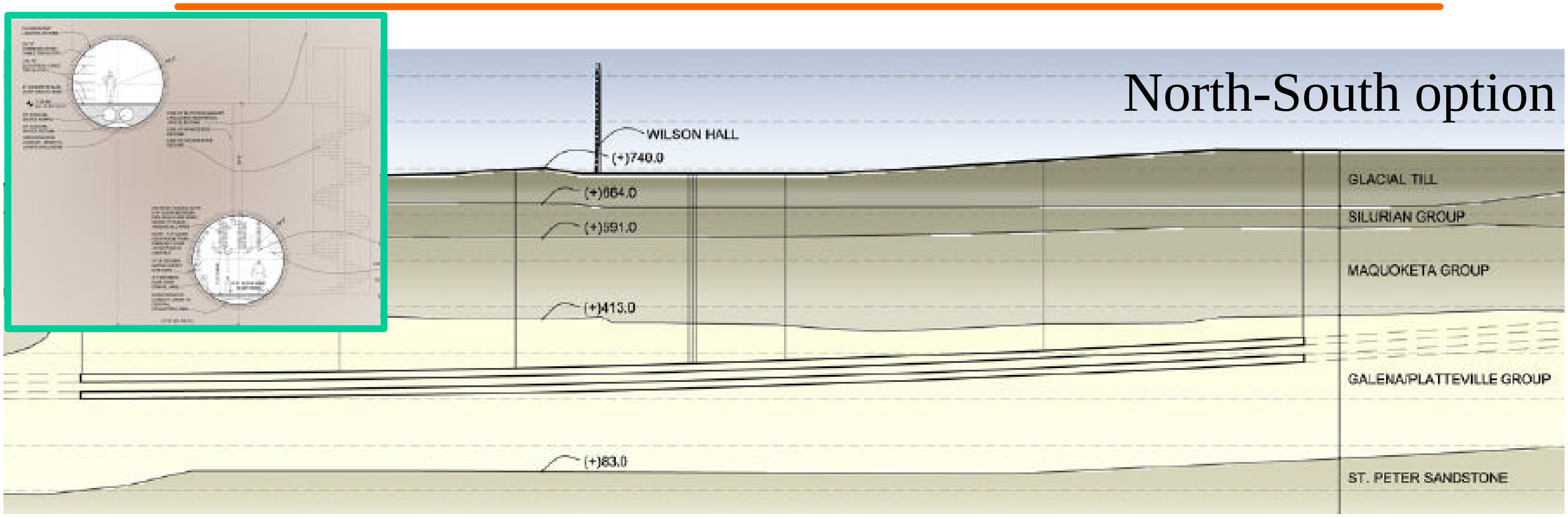
- SLC was hampered by poor reliability in early years
  - Recovery often much longer than length of access
    - example: DR orbit drift with temperature over > 24 hrs
  - Frequent interruptions made progress very difficult
    - during good SLC operation, shutdowns w/ access ~ 6-8 weeks
- NLC designed for high reliability
  - Multiple (redundant) power supplies, electrical/cooling sys.
  - Klystron/modulator repair during physics operation
  - Separate beamline housings limit area affected by access
- A single tunnel is a very risky way to save money!
- The Second ACFA Statement on e+e- Linear Collider (October 2001)
  - "Because of the large number of RF units … The possibility of repairing these components in parallel to the physics run is required to achieve high integrated luminosity"

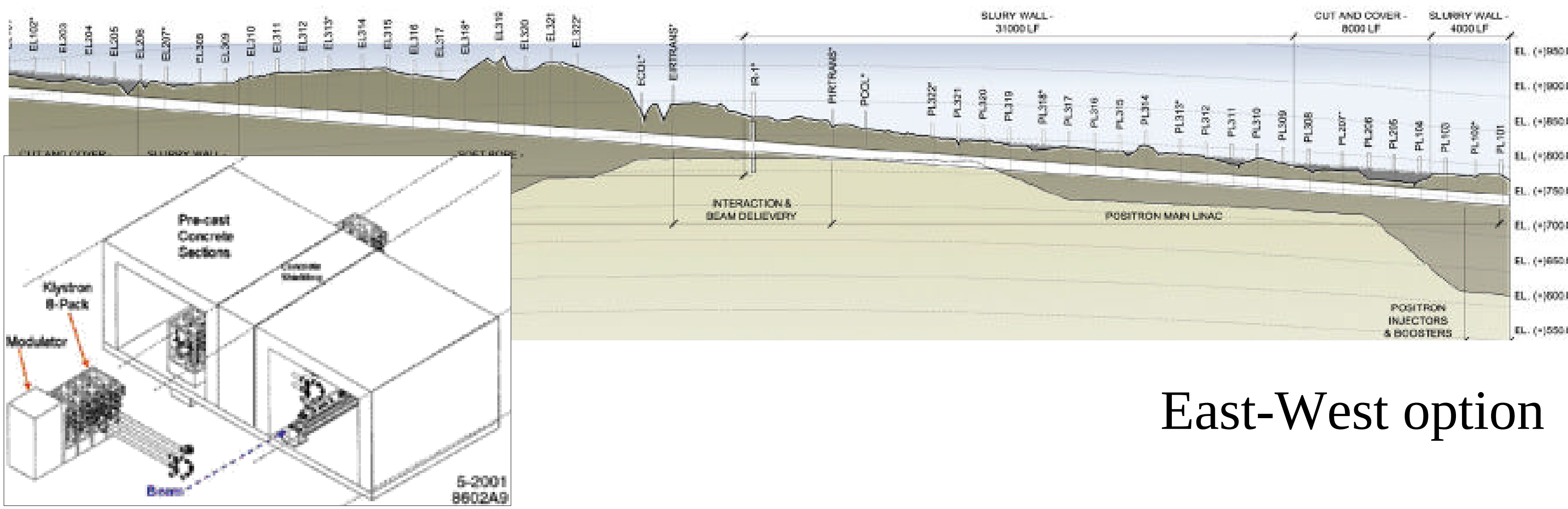
Possible California Site Option





Possible Illinois Site Options





East-West option

International Milestones

HEPAP

- The United States …
  - Strong recommendation in Sub-Panel Report.
  - The "New Reality" in Washington since September 11.
  - DOE, NSF, OSTP will be testing support of broader science community.
  - U.S. Linear Collider Steering Group.

ECFA

- German Wissenschaftsrat reviewing TESLA along with other major physics initiatives (e.g. European Spallation Source), and expected to report in Summer 2002.

ACFA

- Japanese (KEK) will submit request for JLC Project Preparatory funds (rough equivalent of U.S. Conceptual Design) in Fall 2002. Monbusho must weigh against other initiatives (e.g. ITER).

ICFA

- Loew Committee compilation of design and R&D at EPAC in Paris in June 2002.

2001 ICFA Technical Review

- Compare four projects: CLIC, JLC (C), NLC/JLC (X), TESLA
  - 1) Whether any or all of these four approaches can lead to a functional project with the required design and operating parameters,
  - 2) Further R&D that is required

ILC-TRC Steering Committee

Chair: Gregory Loew (SLAC)
Members: Reinhard Brinkmann (DESY)
Gilbert Guignard (CERN)
Tor Raubenheimer (SLAC)
Kaoru Yokoya (KEK)

- Form two working groups:
  - Energy (primarily rf technology but include reliability and upgrade routes)
  - Luminosity (try to evaluate the real luminosity potential)

- Present draft at the European Particle Accelerator Conference, June 2002

TRC Working Groups

Energy & Technology

Daniel Boussard (Chair)

Chris Adolphsen, SLAC
Hans Braun, CERN
Helen Edwards, FNAL
Kurt Hubner, CERN
Lutz Lilje, DESY
Pavel Logatchov, BINP
Ralph Pasquinelli, FNAL
Marc Ross, SLAC
Tsumoru Shintake, KEK
Nobu Toge, KEK
Hans Weise, DESY
Perry Wilson, SLAC

Luminosity

Gerald Dugan (Chair)

Ralph Assmann, CERN
Winifried Decking, DESY
Jacques Gareyte, CERN
Witold Kozanecki, Saclay
Kiyoshi Kubo, KEK
Nan Phinney, SLAC
Joe Rogers, Cornell
Daniel Schulte, CERN
Andrei Seryi, SLAC
Ronald Settles, MPI
Peter Tenenbaum, SLAC
Nick Walker, DESY
Andy Wolski, LBNL

Summary

- NLC and TESLA rf systems are making great progress
  - Rf systems for 500 GeV cms is close to being ready
    - Need to test final prototypes for modules, HOM damping, couplers or pulse compression, and klystrons
    - Need to gain operational time at nominal gradients
  - Rf cavities for 800 – 1000 GeV cms will (?) be ready in 2003
- Luminosity issues are a larger concern!
  - Damping rings are essential for stable operation
  - FFTB and SLC developed instrumentation and techniques necessary for beam-based alignment
  - TESLA linac alignment tolerances are not attainable with proposed conventional systems – need to use NLC-like BBA techniques
  - Beam-beam effects are significant and may force reduction in luminosity in both designs
  - TESLA single tunnel design may severely constrain machine operation

NLC Costs

NLC cost reduced by ~25% since 1999 Lehman review based on technologies that were still being developed in 1999

Costs estimate reviewed for completeness by Lehman NOT for accuracy!

Concern regarding volume discounts!

Present cost estimate is roughly 6B$ including contingency, escalation, labor, G&A, and pre-ops

- → Number of modulators and klystrons reduced by factor of 2
- → Overall system power efficiency improved by 60%
- → Beam Delivery system length halved, with multi-TeV energy reach

Cost for 1 TeV is ~25% additional