

NLC - The Next Linear Collider Project

# NLC Accelerator Design and Critical R&D

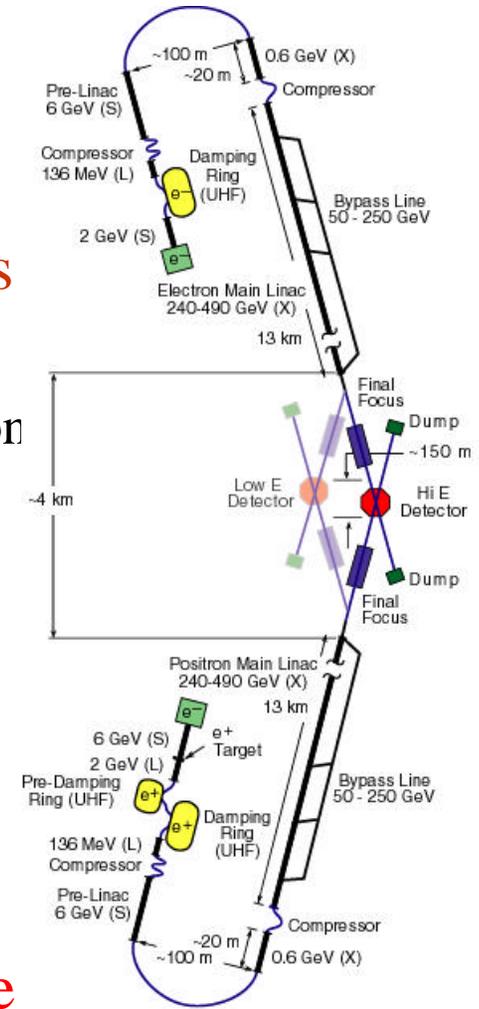
**NLC MAC Review**

**May 10<sup>th</sup>, 2002**

*Tor Raubenheimer*

# Accelerator Design State

- Design updated and documented for Snowmass'01
  - 2001 Report on the Next Linear Collider: A report submitted to Snowmass '01
- There have been a number of optical improvements
  - New pre-damping ring designs
  - Improved final focus and integrated non-linear collimation system (vers. 112)
- Other sections have not been modified since original ZDR design (1996)
- Throughout small inconsistencies in tolerance and performance specifications
- Critical to demonstrate NLC rf system performance
- Is it necessary to update the design?





# LC Technical Review Committee

Two working groups

## Energy & Technology

Daniel Boussard (Chair)

Chris Adolphsen, SLAC ★  
Hans Braun, CERN  
Yong-Ho Chin, KEK  
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  
Winnie Decking, DESY  
Jacques Gareyte, CERN  
Witold Kozanecki, Saclay  
Kiyoshi Kubo, KEK  
Nan Phinney, SLAC ★  
Joe Rogers, Cornell  
Daniel Schulte, CERN  
Andrei Seryi, SLAC ★  
Ron Settles, MPI  
Peter Tenenbaum, SLAC ★  
Nick Walker, DESY  
Andy Wolski, LBNL ★



# LC Technical Review Committee

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- The Technical Review Committee (TRC) has led to extensive review of many NLC subsystems
  - Many NLC people are involved directly or indirectly
  - Technical Systems: present status is being studied (compared)
  - Luminosity Group: breaking new ground (collaborative effort)
    - Mainly damping ring studies and DR → IP luminosity studies
    - Reliability and integrated luminosity performance very difficult
    - Benchmarking simulation codes against each other
    - Pushing to include ‘all’ relevant effects
      - Static alignment procedures
      - Vibration and stability effects with feedback systems
      - Beam-beam effects at IP – [LIAR/DIMAD/GuineaPig](#)
    - Leading to improvements in all designs: TESLA and JLC/NLC



# Linear Collider Design Status

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- NLC and JLC designs need consistent update
- TESLA probably needs the same (luminosity performance studies are far behind JLC/NLC)
- At this point, two approaches:
  - Create common (international) design effort for systems other than the rf systems
    - Rf systems too specialized and driven by national funding
    - Logical continuation of Snowmass and TRC Luminosity group
  - Update NLC design and prepare for cost and schedule analysis
    - Important for detailed comparison between designs
- Regardless of desirability, first option is not possible now and second option is likely necessary



# NLC Design Update (NLC 2004)

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- Goal: be ready with a ‘documented’ design in roughly 2 years to support a technology decision
  - Develop a design that could be the *basis* for a CDR document
    1. Choose between technology options for the baseline, for example
      - PM versus EM in main linac
      - E+ source technology
      - SC versus PM for the final doublet
      - RF system configuration
    2. Document with internal notes and computer records
    3. Prepare for a cost and schedule analysis
  - Most TRC work will finish/wind down this summer
  - Begin internal subsystems reviews late summer
  - Maintain close contact with KEK colleagues

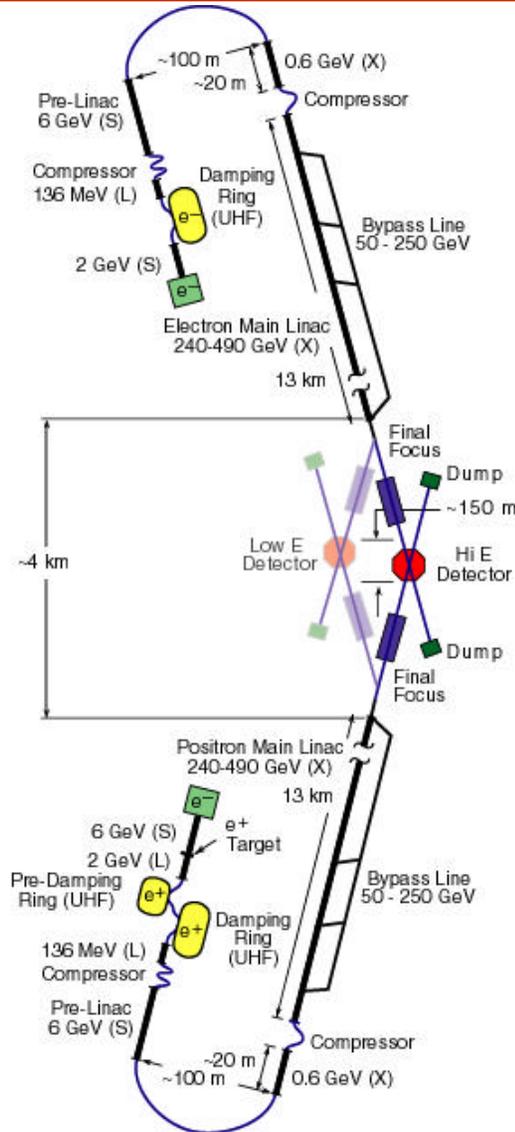


# Funding and Priorities

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- **Budget assumptions**
  - FY2003 will be flat
  - FY2004 will have some growth
- **The RF system and structure gradient R&D are the highest priorities**
  - The remaining program will be squeezed to fit these goals
- **Still substantial technical risk in RF system development**
  - Current schedule completes demonstration in 2004 but is success-oriented and has little or no contingency
  - Important to complete this in a timely manner!
- **Non-RF R&D program has been a strength of NLC design**
  - Still lots of work that must be done – need to prioritize and prune

# Accelerator Physics Issues in NLC



- **Two issues:**
  - Energy (rf technology)
  - Luminosity (small spot and beam power)
- **Beam power (long bunch trains):**
  - Charge from sources
  - Long-range wakefields
  - Radiation damage
- **Small spot sizes:**
  - Low emittance damping rings
  - Final focus system
  - Alignment and jitter tolerances
  - Beam-based alignment and feedback
- **Both issues: (very high charge densities)**
  - Damping ring instabilities
  - Beam collimation and machine protection

# Luminosity:

**only few  $\times 10^4$  larger than SLC!**

$$L = \frac{f_{rep} n_b N^2}{4p \mathbf{s}_x \mathbf{s}_y} H_D \quad \longrightarrow \quad L = \frac{2P_b}{4p E_{cms}} \frac{N}{\mathbf{s}_x \mathbf{s}_y} H_D$$

- Increased beam power from long bunch trains
  - SLC: 120 Hz x 1 bunch @  $3.5 \times 10^{10}$
  - NLC: 120 Hz x 190 bunches @  $0.75 \times 10^{10} \rightarrow 200x$
  - TESLA: 5 Hz x 2820 bunches @  $2.0 \times 10^{10} \rightarrow 340x$
  - Control of long-range wakefields is essential to assure multi-bunch
- Larger beam cross-sectional densities:  $N / (\sigma_x \sigma_y)$ 
  - SLC:  $3.5 \times 10^{10} \times 1.6 \mu\text{m} \times 0.7 \mu\text{m}$  (FFTB:  $0.6 \times 10^{10} \times 1.7 \mu\text{m} \times 0.06 \mu\text{m}$ )
  - NLC:  $0.75 \times 10^{10} \times 250 \text{ nm} \times 3.0 \text{ nm} \rightarrow 330x \text{ SLC}$
  - TESLA:  $2.0 \times 10^{10} \times 550 \text{ nm} \times 5 \text{ nm} \rightarrow 230x \text{ SLC}$
  - Factor of 5 from energy (adiabatic damping) and factor of 10 from stronger focusing (similar to Final Focus Test Beam) but higher energy
  - Factor of 15 ~ 30 from decrease in beam emittance!

# Sources and Damping Rings

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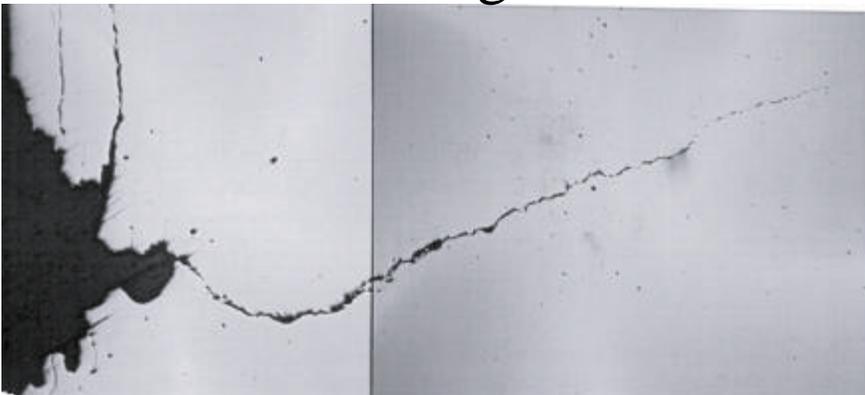
- Sources: Based on SLC designs
  - Current Limit from e- photocathode is OK
  - Positron target survival (SLC target failed early) understood
  - Designed to avoid known SLC limitations
  - Difficulties with beam power and radiation
  - Beam loading will be large -- OK in simulation
- Damping rings: ATF at KEK is a close prototype
  - Similar to 3rd generation light sources or HEP factories
  - Complicated accelerator physics
    - Emittance tuning and BBA are difficult!
    - Injection/extraction are difficult
    - Very sensitive to instabilities
      - DR's were 'the source of all evil' in the SLC
    - Push new limits on charge density



# E+ and E- Sources

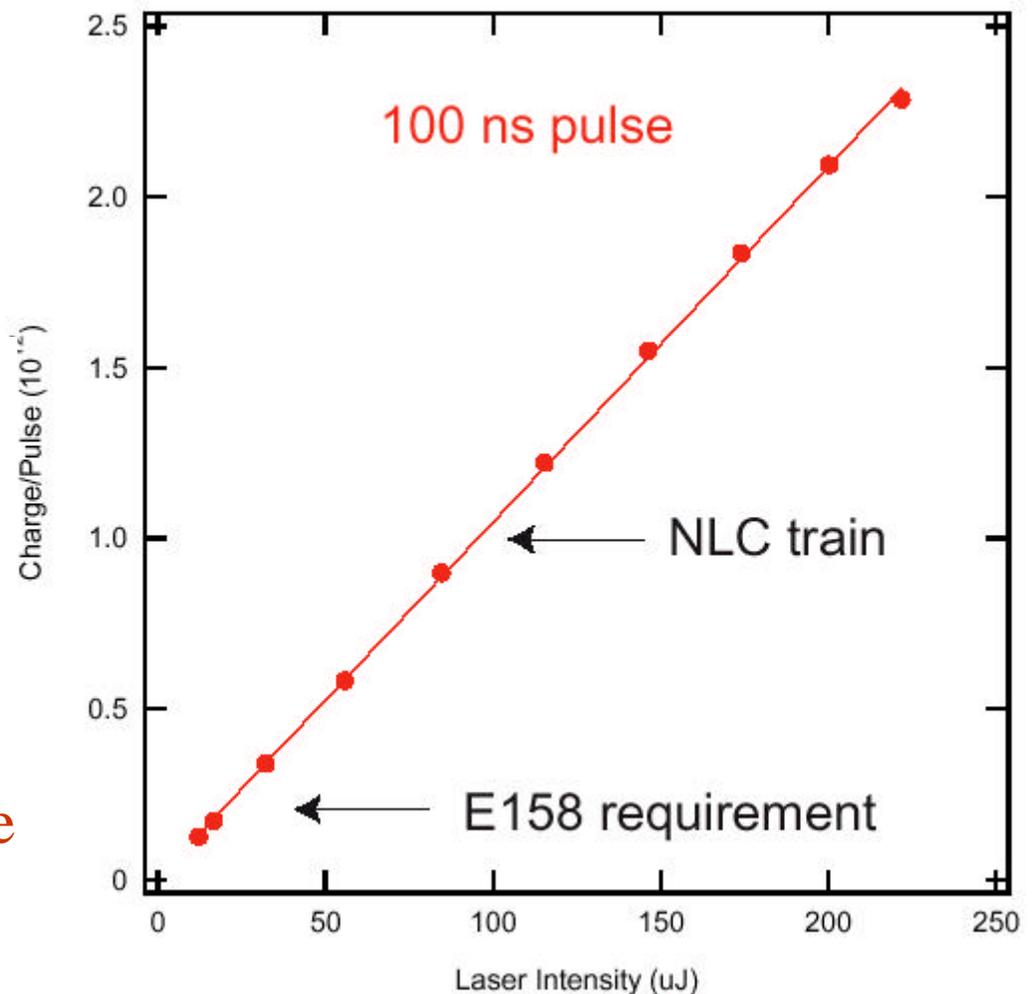
- Demonstrated charge and polarization in E158 test
- Brute force solution to e+ target limitations

SLC e+ target



- Other e+ sources possible but not a high priority

E158 Photocathode



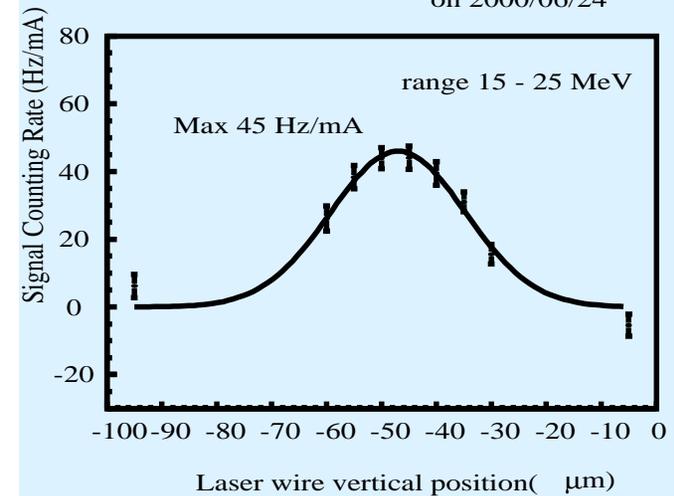


# ATF Damping Ring at KEK

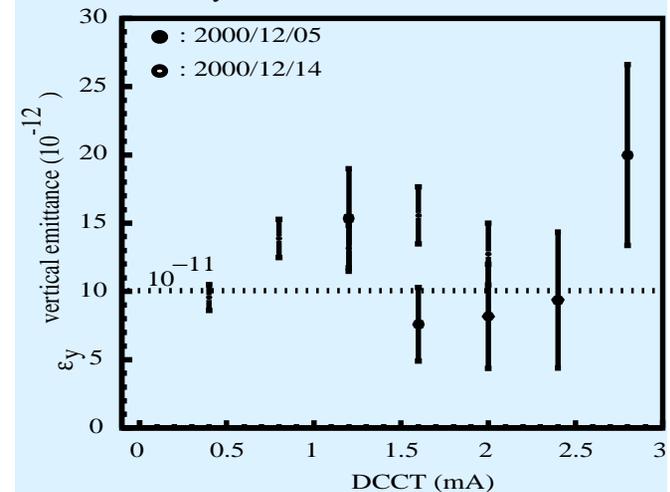
Vertical emittance  $3.5 \times 10^{-8}$  measured with laser wire ( $\sim 2 \times$  NLC spec)



Measurement of the vertical beam size on 2000/06/24



Summary of vertical emittance measurement

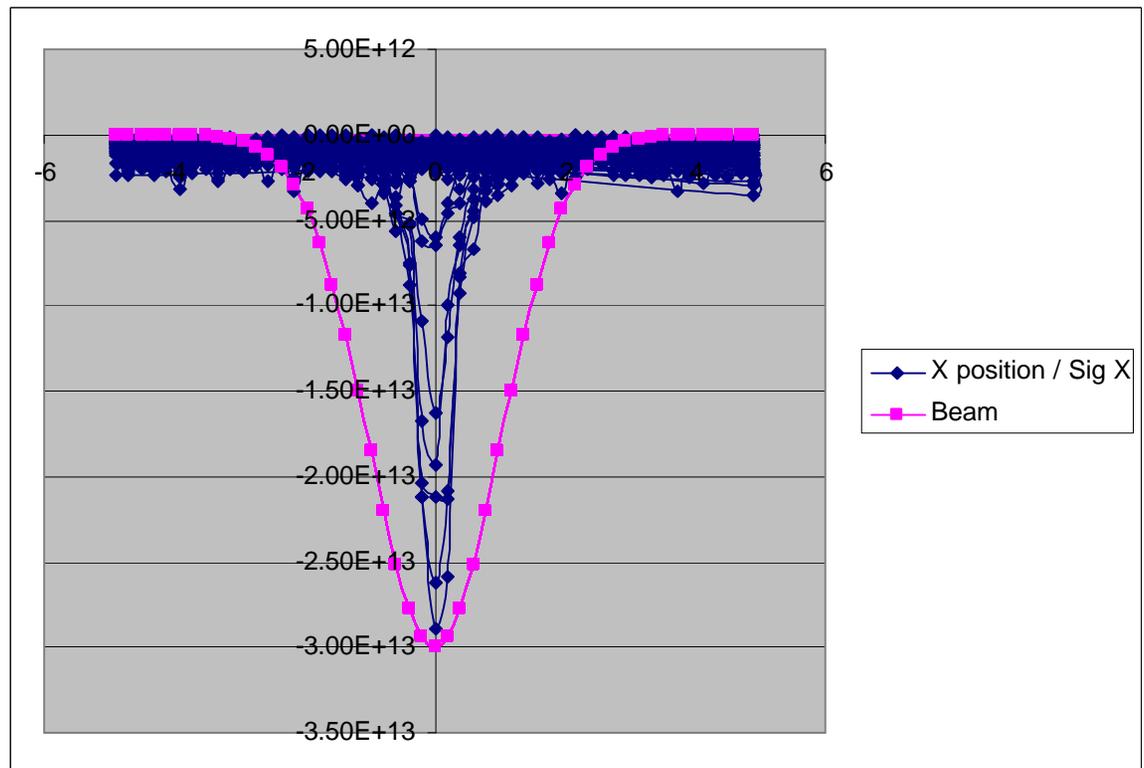




# Ion and Electron Cloud Effects

- Concerns about control of vertical emittance
- Estimates for NLC and TESLA predict electron cloud induced incoherent tunes spreads of 0.30 and 8, respectively
- Estimates predict ion induced tunes spreads of 0.01 and 0.06 in NLC and TESLA
  - This is bad enough!

Cloud density in beam



## Damping Ring R&D

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- Achieving the vertical emittance ( $\sim 0.5\%$  coupling ratio) requires much better alignment than typically in storage rings
- Incoherent space charge tune shift is  $\sim 0.05!$
- Intrabeam scattering becomes significant with high densities
- Touschek lifetime is a few minutes
- Old instabilities:
  - Microwave – bursting instability has huge effect downstream
  - Transient loading – impacts bunch compressor designs
  - Coupled bunch – need feedback with very high power but low noise in transverse and longitudinal
- New instabilities:
  - Electron cloud – initial simulations show tune spreads  $\sim 1$
  - Ions – fast coupled bunch growth rates with few solutions
  - New dynamics from large wiggler radiation??



# Bunch Compressors

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- **Bunch compressors:**
  - BC1 similar to SLC compressor
  - BC2 complicated manipulation in longitudinal phase space
    - Constructed from simple FODO arc and chicane
    - Tuning simulations show wide range of operation
  - Improved optics to avoid known SLC problems with high-order optics
  - CSR effects predicted to be small
  - Tight alignment tolerances - similar to main linac
    - Global tuning worked well in ZDR and early design
    - Need further studies
  - Large filamentation - must control injection orbits
    - Requires good feedback systems
  - Very tight tolerances on rf phases
    - $\Delta\phi < 0.5$  degrees

# Main Linacs

- Main Linacs
  - Improved optics to avoid known SLC problems with chromatics
  - BBU from short- and long-range wakefields must be controlled
    - ASSET measurements verify procedure
  - Machine protection will be difficult
    - Requires good feedback systems
    - Complicates turn-on and recovery
  - Tight alignment tolerances
    - Studied extensively (See PT's talk last November)!
    - Have multiple solutions with backup plans
    - Sets tight requirements on diagnostics and controls
    - Demonstrated similar alignment at FFTB
    - Demonstrated emittance tuning at SLC
  - Will require excellent stability (both vibration and drift)
    - Need to verify ATL and cultural noise

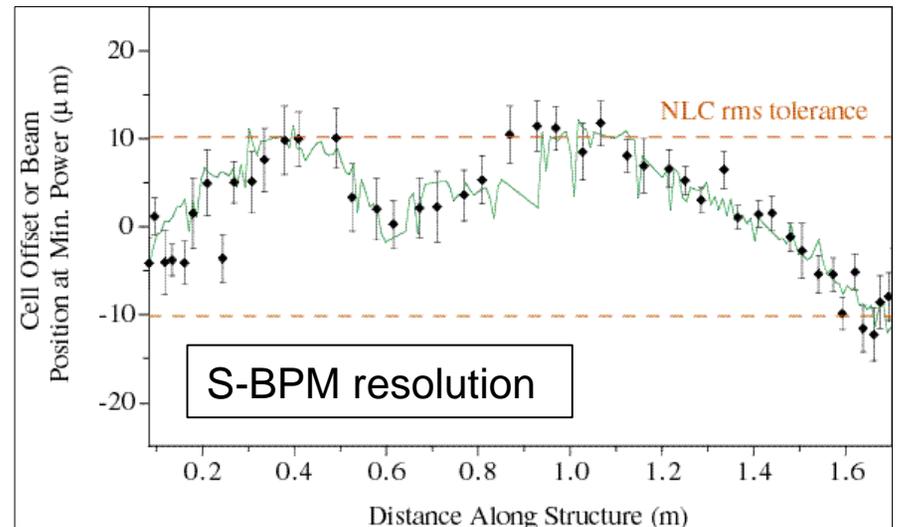
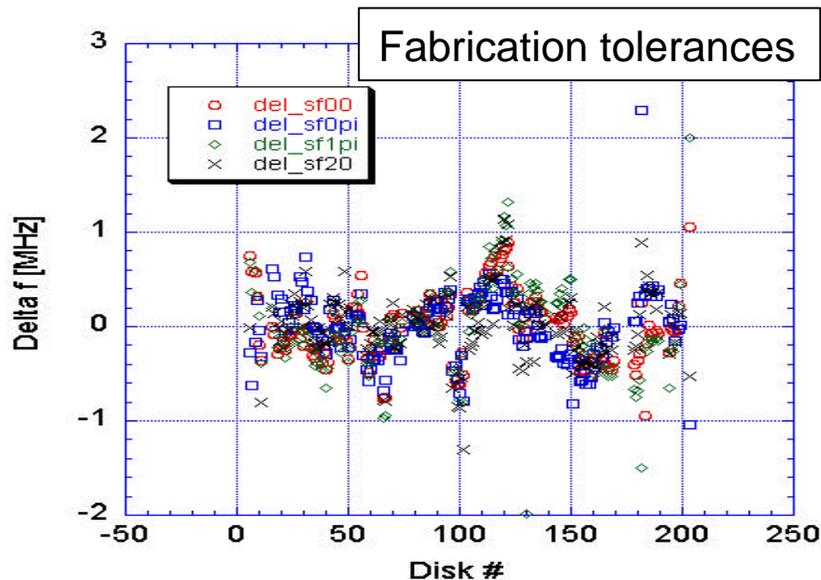
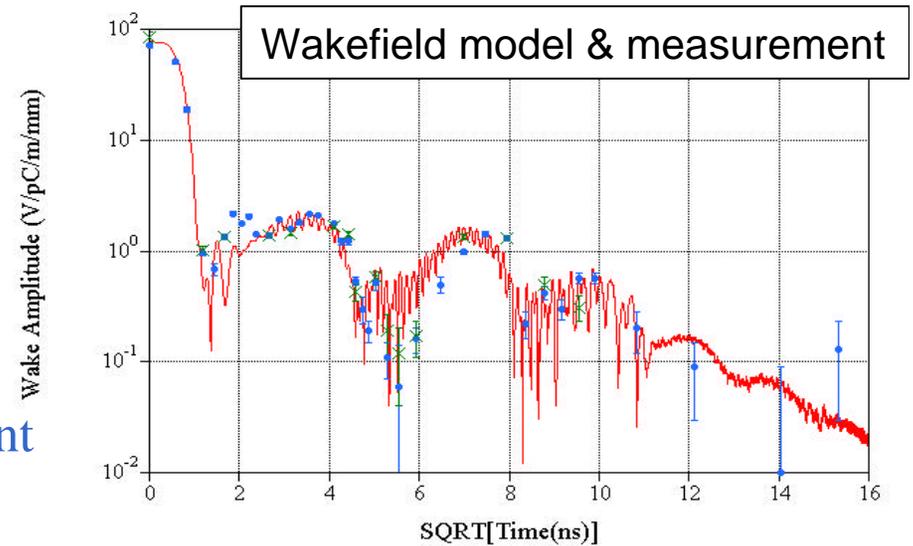


# Structure Design Issues

Precision wakefield measurements agree well with model prediction

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

Structure BPM achieved  $< 1 \mu\text{m}$  centroid resolution (tol.  $20 \mu\text{m}$ ) – essential for alignment





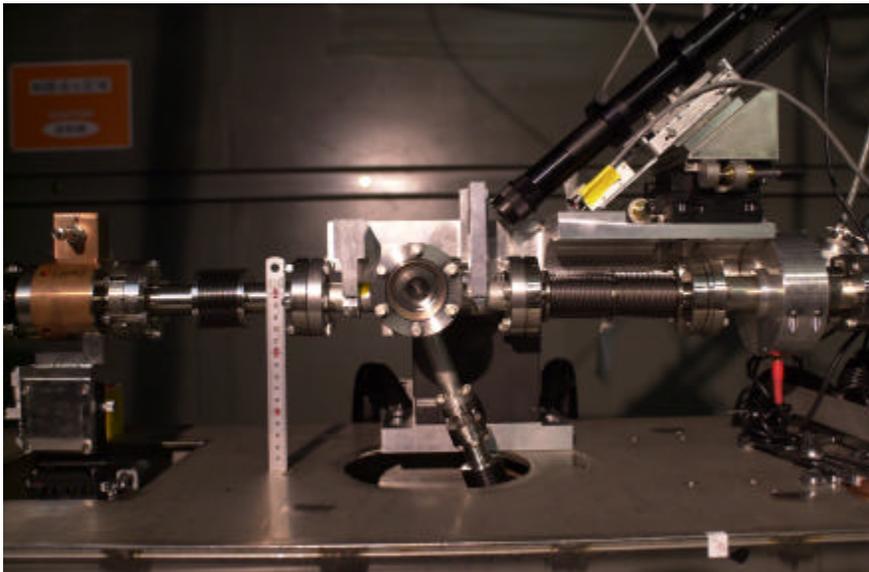
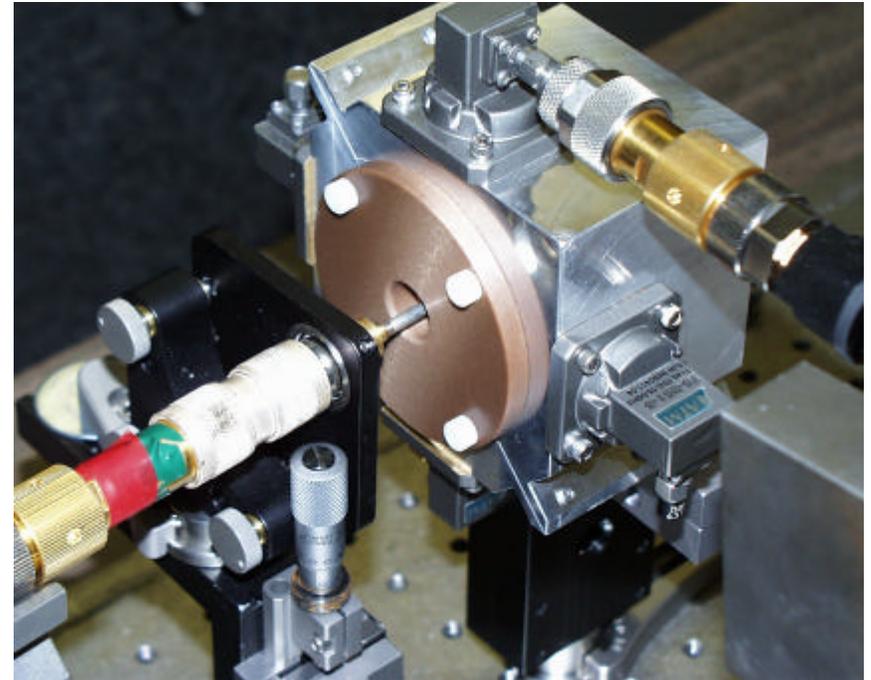
# Beam-Based Alignment

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- Alignment tolerances in NLC/JLC are very tight!
  - 1 - 10  $\mu\text{m}$  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  $\mu\text{m}$  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 is essential for convergence!

# Instrumentation Development

- High-res. instrumentation developed for FFTB
- More recently RF linac-style BPM with 230 nm resolution!
- OTR BSM being tested at KEK ATF

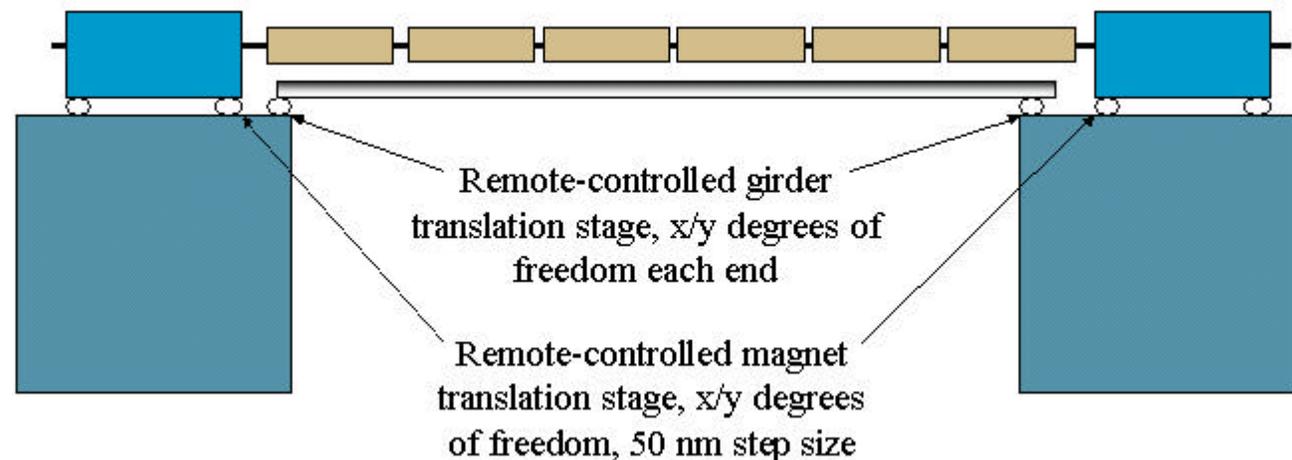


- Instrumentation is essential for LC operation and BBA
- Close to required specs.

# Main Linac Vibration

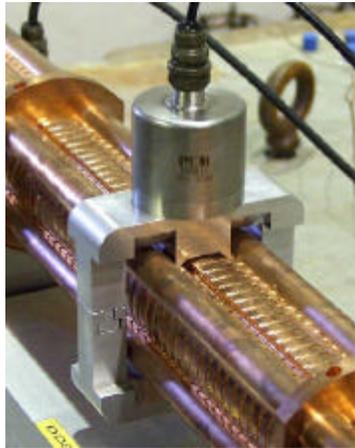
- Measurements at the Final Focus Test Beam show that coolant flow is not a large source of quadrupole vibration
- Coolant in accelerator structures may be a large source of vibration and RF waveguides connect to large vibration sources
  - Vibration tolerances on the structures is very loose ( $\mu\text{m}$ 's)
  - Structures are connected to the quadrupoles through the vacuum chamber and the pedestals

Beam-based  
alignment view  
of a linac girder

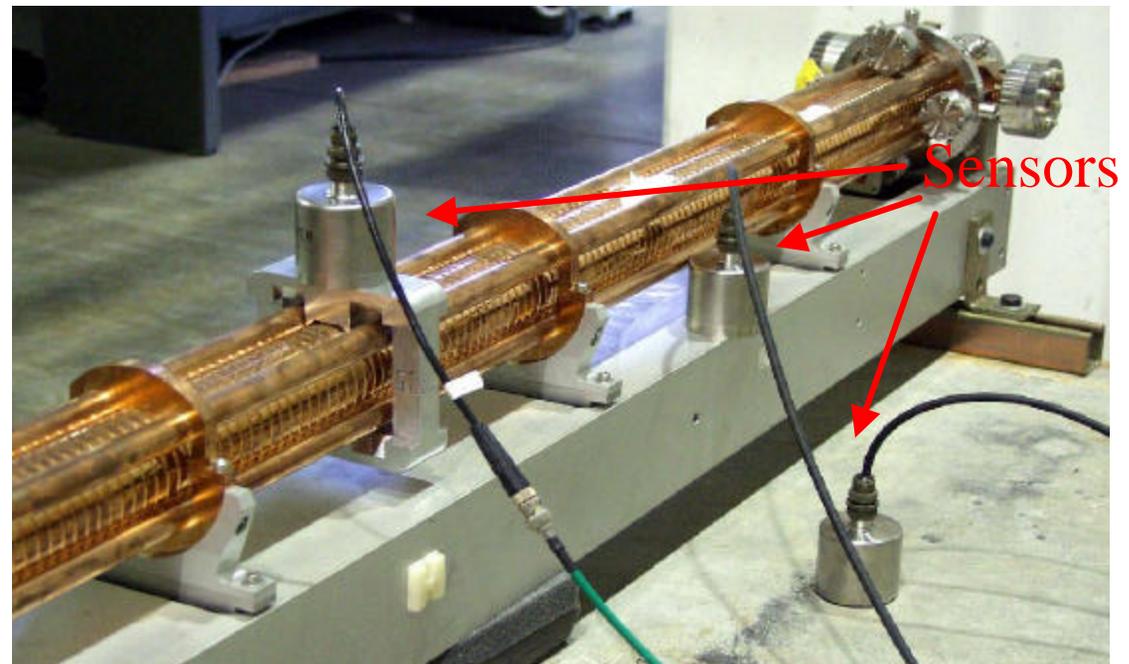
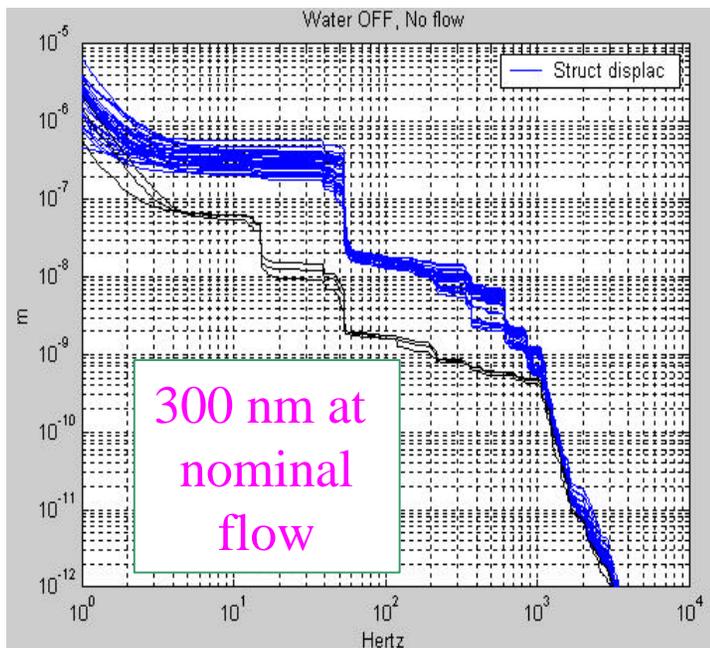




# Structure Vibration Study



- Vibration of accelerating structure caused by turbulent water flow
  - Estimate of vibration (simplified & pessimistic) gave **1mm** amplitude
  - This is below tolerances for structure itself, but must worry about **coupling** of structure to quad where the tolerance is  $\sim 10$  nm





# Main Linac Stability

- Need to have stable operation for BBA and  $\epsilon$  tuning as well as tuning of the final focus system
- Add new results from MI8 ATL study

Place	$\Delta$ mm <sup>2</sup> /(m.s)
HERA R.Brinkmann, et al.	$\sim 10^{-5}$
FNAL surface V.Shiltsev, et al.	$(1-10) * 10^{-6}$
SLAC*	$\sim 5 * 10^{-7}$
Aurora mine* V.Shiltsev, et al.	$(2-20) * 10^{-7}$
Sazare mine S.Takeda, et al.	$\sim 5 * 10^{-8}$

NLC: Undisruptive  
realignment ~every 5hrs

NLC: Undisruptive  
realignment ~every 2 days

\* Further measurements in Aurora mine, SLAC & FNAL are planned



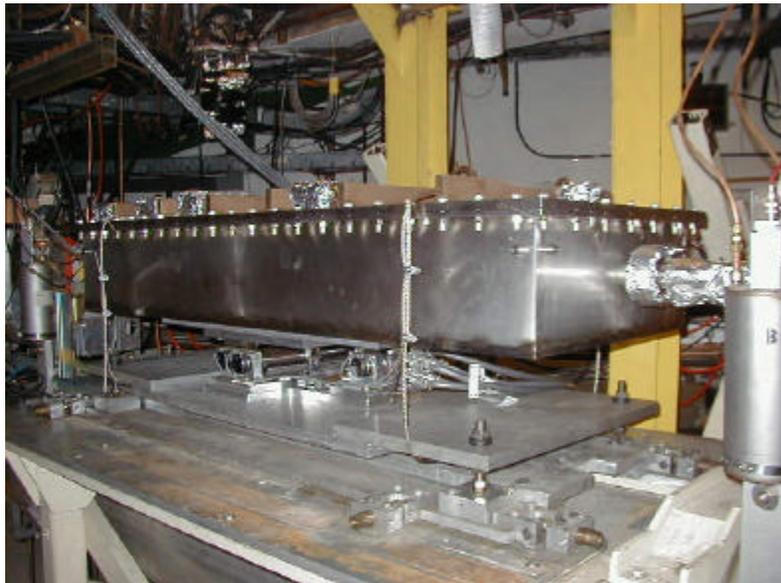
# Beam Delivery System and Collimation

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- **Beam Delivery System**
  - **Optical demagnification and high-order cancellation of aberrations demonstrated at FFTB**
    - All optical aberrations will demagnify with emittance
    - Optics codes verified for beam core transport
  - **Prototyped consumable spoilers and measured collimator wakes**
    - Still more work needed but certainly believable at this point
  - Most magnet tolerances comparable to linac magnets
  - Final doublet using PM possible although not elegant!
  - **Nonlinear collimation system eases collimator requirements greatly**
    - Requires very good knowledge of aberrations at  $100+ \sigma$
  - **Final focus tuning requires stable beam from linacs and at IP**
  - **Final doublet vibration tolerances  $\sim 1\text{nm}$** 
    - Motion in the detector will certainly exceed this level!

# Collimator Studies

- Studied geometric and resistive wakefields
  - apparatus in ASSET region of SLAC linac
  - Led to development of new theory for geometric wakes
  - Studied graphite spoilers from DESY

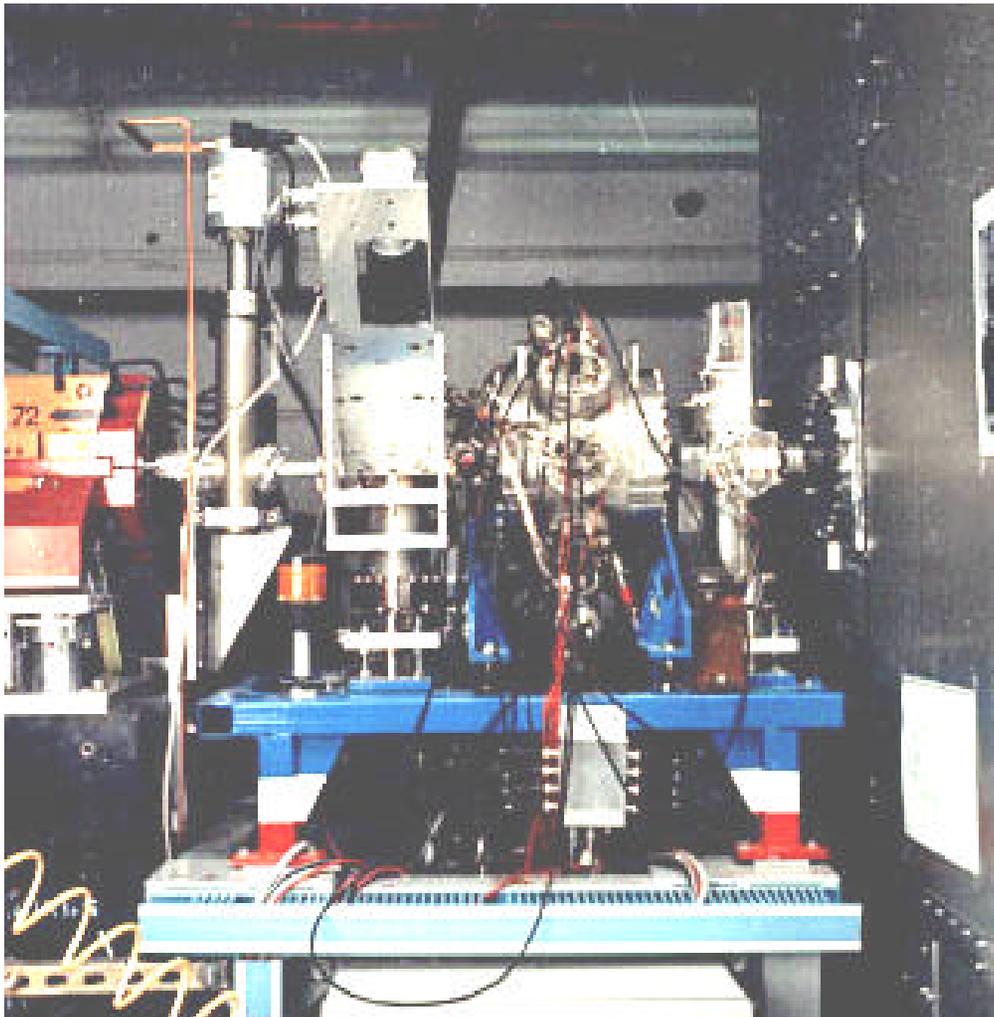


- Built prototype of a ‘consumable’ collimator



# Vibration at IP

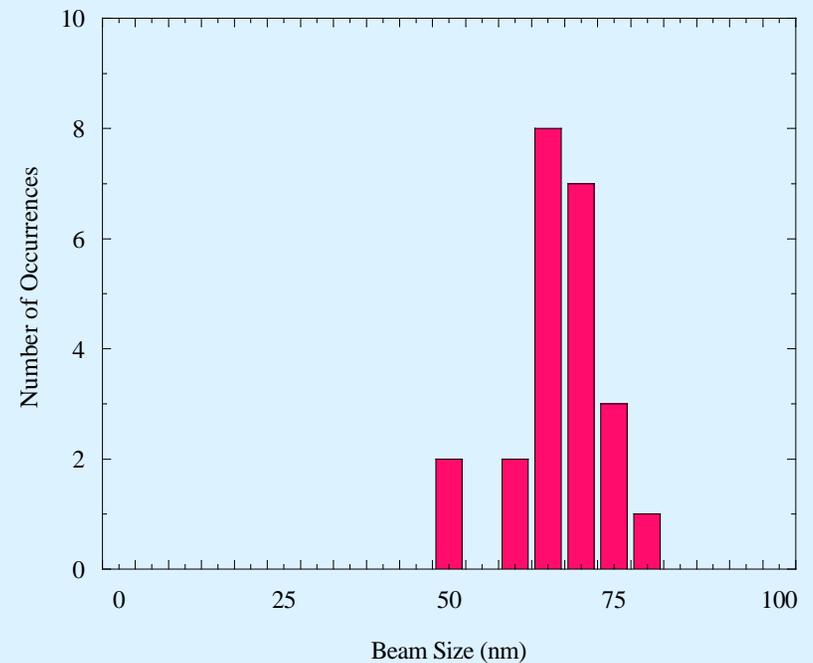
## FFTB IP



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

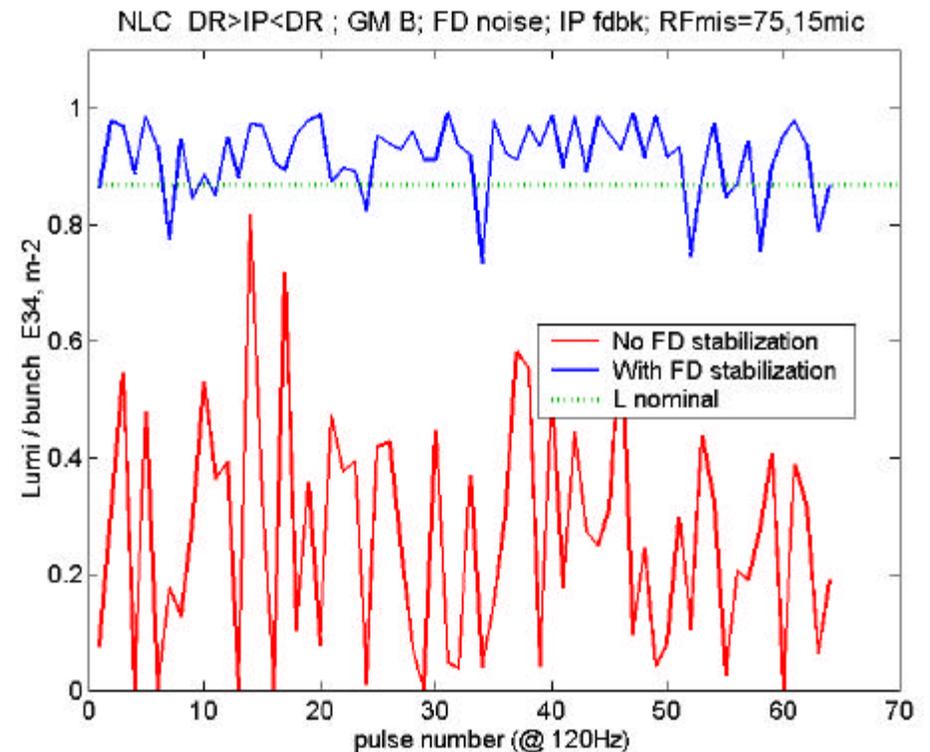
Demonstrated precise diagnostics!

**BUT measured 40 nm vibration!**



# IR Magnet Girder

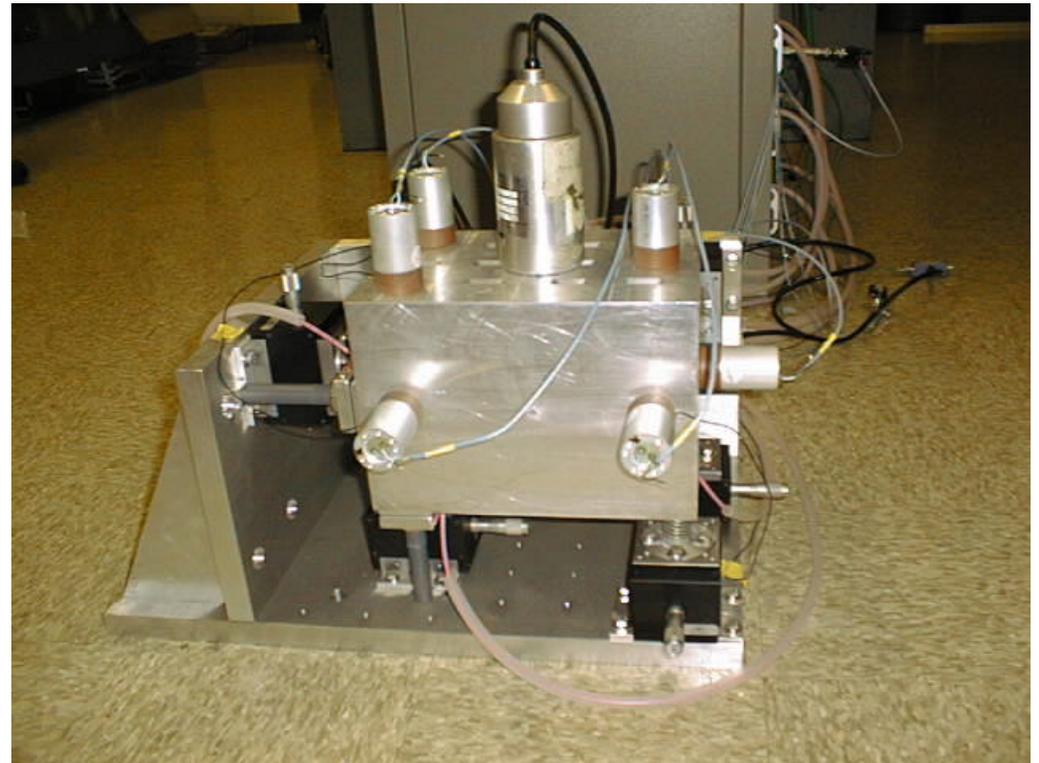
- The vertical spot size in NLC is 3nm at 500 GeV cms
  - Motion of the strong final focusing magnets needs to be  $<2$  nm!
    - Natural ground motion might be OK
    - Measurements on SLD are  $\sim 20$ nm
    - Strong coupling between detector solenoid and IR quads
    - Must stabilize final quadrupole magnet for incoming beams
  - Develop fast intra-train feedback to provide margin
    - Collaboration with Oxford University



# Stabilization Studies

- Inertial system with 6 d.o.f. tested at SLAC
  - Limitation due to sensors
  - Reduced vibration  $>10x$
  - Performance will depend on beam-beam feedback system
- Optical anchor system studied at SLAC and UBC
- Both systems have demonstrated feasibility
  - Need to start considering 'real' implementation

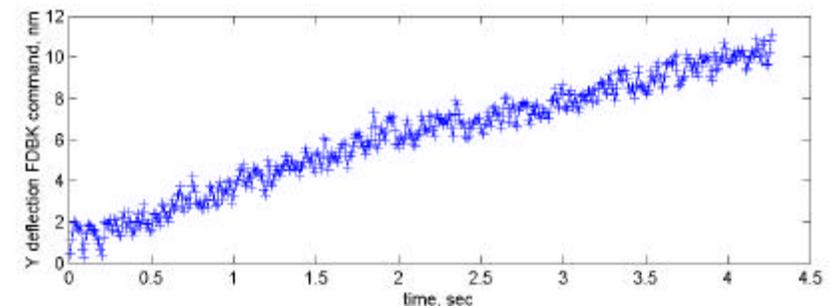
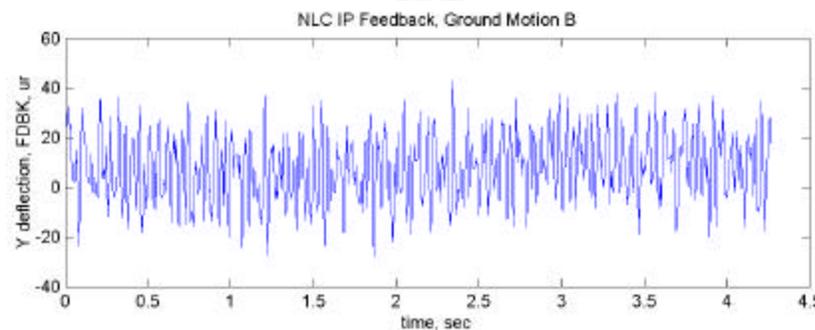
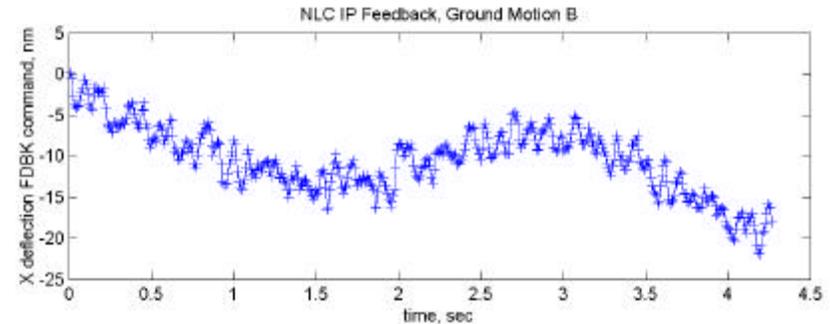
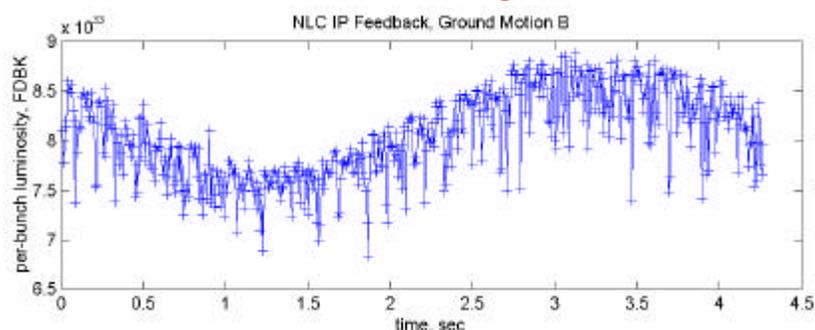
Inertial Stabilization Test Block





# Beam-Based Feedback Studies

- Many studies of linac feedback systems
  - Usually based on ‘SLC’ feedback model
  - Optimized for noise spectrum at SLC – lots of high freq. noise
  - Not very aggressive but robust to errors
- Started studying IP feedback using two colliding beams and GuineaPig with different ground motion models



# Stability and Vibration

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While it is important to demonstrate stabilization at this level before committing to the final design of the final focus system, this is not an issue that affects the fundamental viability of the NLC project. Thus, given the scarcity of resources, it is not necessary to pursue this problem vigorously at this point.

- This is absolutely true when one considers the direct impact on the luminosity
- However, beam stability is absolutely essential for tuning and without beam-based tuning, this collider will deliver zero luminosity!

## Non-Rf Accelerator Design R&D

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- Previously had a broad R&D program to address issues relevant to LC other than RF power
  - Many issues already demonstrated or nearly demonstrated: wakes; movers; instrumentation
  - Polarized e- photocathode developed
  - e+ target analysis at LANL and LLNL
  - FFTB coupon tests to study materials damage
  - KEK ATF damping ring collaboration
  - IBS experiments at ATF at KEK and ALS at LBNL
  - Permanent and electromagnet quadrupole studies
  - ASSET and collimator wakefield test facility
  - ‘Consumable’ collimator prototype
  - Hydrostatic leveling system developed at BINP/FNAL/SLAC
  - Active isolation systems at UBC and SLAC
  - Intra-train feedback being developed by Oxford



# Primary Topics for R&D

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- **Important non-rf system questions:**
  - Linac and FFS stability issues (drift and vibration)
    - Existing diagnostics and controls for beam-based alignment (BBA) are very close to what is required for NLC
    - Multiple layers of BBA techniques giving confidence in the static solutions BUT how long will they be stable?
    - Vibration of sites is perfectly adequate for most of NLC
      - Requirements of IR magnets is 10x tighter
      - Cultural sources could easily exceed vibration budgets
    - Demonstrate IP stabilization and measure linac girder vibration sources
  - Damping ring performance questions
    - Instabilities in the damping rings could limit operation
    - Rings are similar to 3rd generation light sources but are wiggler ‘dominated’ with new dynamics

## Secondary Topics for R&D

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- Rf power at FNAL
  - To test structures and develop x-band knowledge FNAL needs an x-band rf power source
- E+ generation
  - Brute force approach may be expensive and operationally difficult
  - Undulator scheme has performance limitations
  - Compton backscatter is very difficult
- High-order optics (FFS and nonlinear collimation)
  - Believe optics calculations for beam core
    - Mostly demonstrated at FFTB and SLC
    - Most aberrations scale with incoming emittance
  - To understand beam tails need to optics predictions at  $>100 \sigma$

# Non RF System R&D Program

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- Focus the R&D program to more closely support the design
  - With the exception of the rf system, we are currently pursuing a broad program of small projects aimed at verifying feasibility
    - Focus this towards a few larger programs which will ultimately evolve into demonstrations
    - Encourage external (university) collaborators to participate in these larger projects
- Develop program aimed at major issues:
  - Damping rings
  - Linac and FFS stability and site characterization
- Programs should be chosen to answer well defined issues or designed to evolve into full demonstrations
  - IBS and ion instabilities: need detailed exp. to measure growth rates
  - FFS stability: develop IP support demonstration



# Collaboration with KEK

- Established common beam parameters
- Working together on gradient limitations
- Collaborate on ATF damping ring prototype
- Have similar rf systems – discussing closer collaboration
- Reviewing each others LC cost and schedule

	Stage 1		Stage 2	
CMS Energy (GeV)	500		1000	
Site	US	Japan	US	Japan
<b>Luminosity (<math>10^{33}</math>)</b>	<b>20</b>	<b>25</b>	<b>30</b>	<b>25</b>
Repetition Rate (Hz)	120	150	120	100
<b>Bunch Charge (<math>10^{10}</math>)</b>	<b>0.75</b>		<b>0.75</b>	
Bunches/RF Pulse	192		192	
Bunch Separation (ns)	1.4		1.4	
<b>Eff. Gradient (MV/m)</b>	<b>48.5</b>		<b>48.5</b>	
Injected $\gamma\epsilon_x / \gamma\epsilon_y$ ( $10^{-8}$ )	300 / 2		300 / 2	
$\gamma\epsilon_x$ at IP ( $10^{-8}$ m-rad)	360		360	
<b><math>g_e y</math> at IP (<math>10^{-8}</math> m-rad)</b>	<b>4</b>		<b>4</b>	
$\beta_x / \beta_y$ at IP (mm)	8 / 0.11		13 / 0.11	
<b><math>S_x / S_y</math> at IP (nm)</b>	<b>243 / 3.0</b>		<b>219 / 2.3</b>	
<b><math>q_x / q_y</math> at IP (nm)</b>	<b>32 / 28</b>		<b>17 / 20</b>	
$\sigma_z$ at IP (um)	110		110	
$\gamma_{ave}$	0.14		0.29	
Pinch Enhancement	1.51		1.47	
Beamstrahlung $\delta B$ (%)	5.4		8.9	
Photons per e+/e-	1.3		1.3	
Two Linac Length (km)	12.6		25.8	

# US NLC Collaboration

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- **FNAL working on NLC linac beamline components**
  - Focusing on structure production
  - Goal: produce two linac rf girders (2 x 5.4 meters) for rf test
  - Leading review of TDR and TESLA costing methods
- **LLNL building modulators and designing  $\gamma$ - $\gamma$  IR**
  - Interested in directly participating in rf systems tests
  - Interested in working on IP girder stabilization project
- **LBNL focused on damping ring design**
  - Leading DR effort
  - Also working on magnet designs
- **BNL will develop compact superconducting quadrupoles for possible IR application**
- **Other groups at: NW, Oxford, UBC, BINP, other University**

# Summary

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- **8-Pack and Gradient R&D are 1<sup>st</sup> priority**
  - Difficult with flat FY2003 funding profile
- **Non-rf R&D program has been very broad and addressed most issues**
  - Real strength of the NLC design
  - Currently comprises about 20~25% of the NLC program
  - This funding will decrease with 8-pack program
- **With 8-pack program, need to focus the non-rf R&D program onto essential outstanding items**
  - IP and linac vibration and stability issues
  - Damping ring accelerator physics and damping ring stability
- **Working through this process!**
  - See talks by Wolski, Markiewicz, Carter, Himel, Seryi