# X-Band Linear Collider

**Path to the Future**

# NLC Luminosity and Accelerator Physics

Tor Raubenheimer

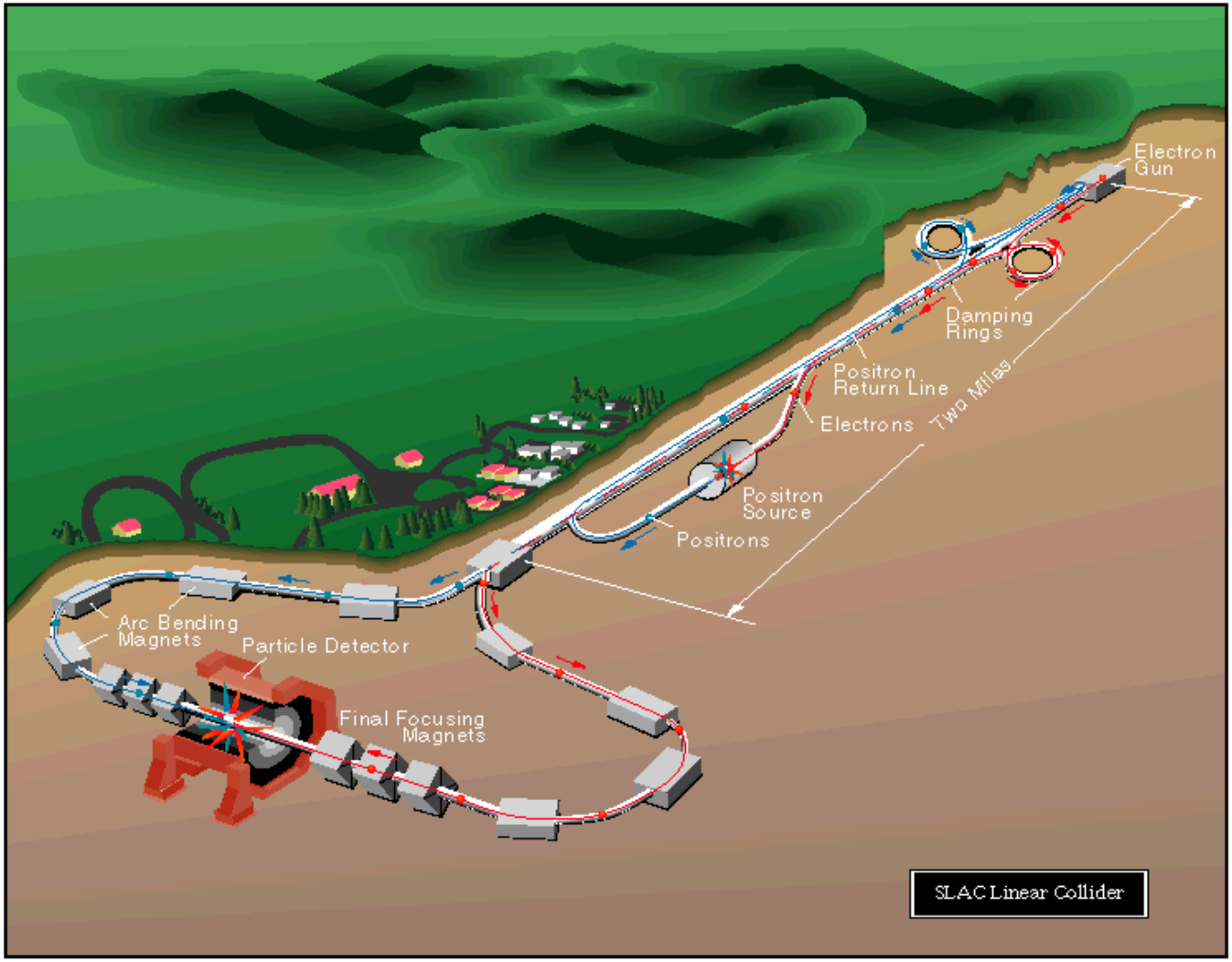
# Outline

- Talk will focus on luminosity design
  - Chris Adolphsen will discuss the rf hardware

1. Lessons from the SLC
2. Performance for peak luminosity
   - Beam emittance generation and preservation
   - Beam power issues
3. Design headroom and luminosity upgrade potential

- All aspects of the GLC/NLC design have been studied
  - Heavily based on experience (good and bad) from the SLC
  - Conservative design → rapid commissioning and luminosity

# First Linear Collider: SLC




Built to study the $Z_0$ and demonstrate linear collider feasibility

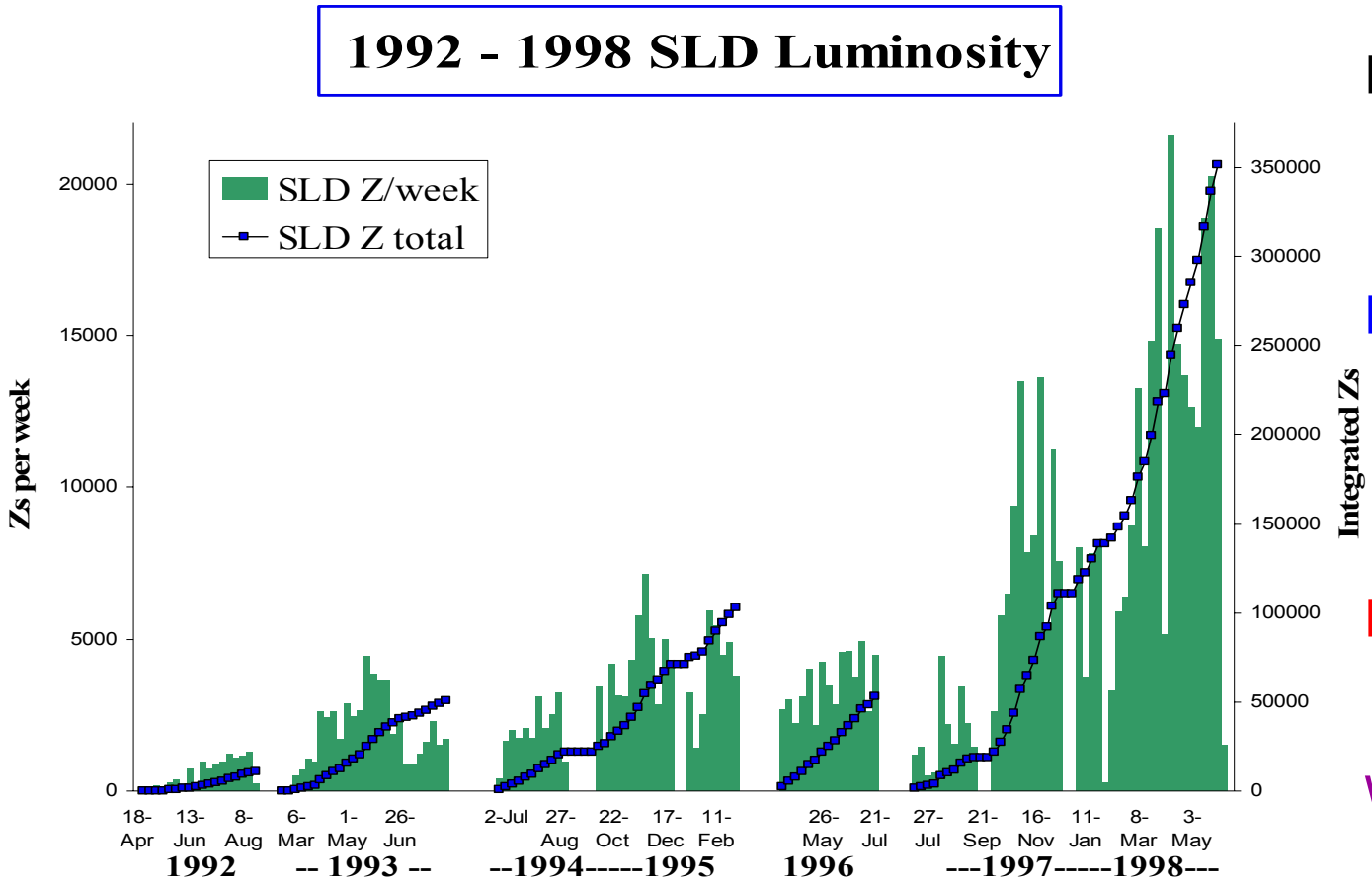
Energy = 92 GeV

Luminosity = 3e30

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

Much more than a 10% prototype

# SLC Luminosity
## Many Lessons Learned




Flexible design to allow parameter optimization

Extensive diagnostics for troubleshooting and tuning

Reliable and stable operation

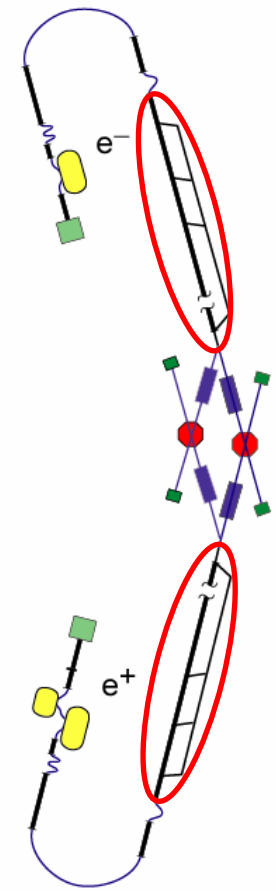
Well designed collimation to limit backgrounds

→ Provides the basis for the next generation LC

# Peak Luminosity
## ~7,000 times larger than SLC

$$L = \frac{f_{rep}}{4\pi}\frac{n_b N^2}{\sigma_x \sigma_y} H_D \quad \Rightarrow \quad L = \frac{P_b N}{4\pi mc^2}\frac{H_D}{(\beta_x \beta_y)^{1/2}(\gamma\varepsilon_x \gamma\varepsilon_y)^{1/2}}$$

- Focusing $(\beta_x * \beta_y)^{-1/2}$ NLC/SLC → 3
  - ✓ Demonstrated at FFTB
- Disruption $H_D$ NLC/SLC → 0.7
  - ✓ Demonstrated at SLC
- Emittance $(\gamma\varepsilon_x * \gamma\varepsilon_y)^{-1/2}$ NLC/SLC → 85
  - Low Emittance Transport and Damping rings
- Beam power term $(P_b * N)$ NLC/SLC → 35
  - Bunch trains, Particle sources, Collimation and MPS
- Integrated luminosity → Tom Himel this afternoon



# Luminosity Comparison with SLC

| | | | | | | | Enhancement Factors | |
|---|---|---|---|---|---|---|---|---|
| | UNITS | SLC | GLC/NLC | TESLA | NLC/SLC | TESLA/SLC | NLC/SLC | TESLA/SLC |
| E_cm | GeV | 92 | 500 | 500 | 5.43 | 5.43 | | |
| f_rep | Hz | 120 | 120 | 5 | | | | |
| n_b | | 1 | 192 | 2820 | | | | |
| N | | 4.10E+10 | 7.50E+09 | 2.00E+10 | 0.18 | 0.49 | | |
| H_d | | 2 | 1.43 | 2.1 | 0.72 | 1.05 | | |
| | | sqrt(e+ x e-) | | | | | | |
| Inj_Inv_Emit_x | 10^-8 m-rad | 3834.1 | 300 | 800 | 0.08 | 0.21 | 3.57 | 2.19 |
| Inj_Inv_Emit_y | 10^-8 m-rad | 259.8 | 2 | 2 | 0.01 | 0.01 | 11.40 | 11.40 |
| | | | | | | | | |
| IP_Inv_Emit_x | 10^-8 m-rad | 6144.3 | 360 | 1000 | | | | |
| IP_Inv_Emit_y | 10^-8 m-rad | 1715.2 | 4 | 3 | | | | |
| Dilution-X | | 1.60 | 1.20 | 1.25 | 0.75 | 0.78 | 1.16 | 1.13 |
| Dilution-Y | | 6.6 | 2.00 | 1.50 | 0.30 | 0.23 | 1.82 | 2.10 |
| BetaX | mm | 3.3 | 8 | 15 | 2.42 | 4.55 | 0.64 | 0.47 |
| BetaY | mm | 2.6 | 0.11 | 0.4 | 0.04 | 0.15 | 4.86 | 2.55 |
| IP Divergence-x | urad | 454.8 | 30.3 | 36.9 | | | | |
| IP Divergence-y | urad | 270.7 | 27.3 | 12.4 | | | | |
| sig_x | nm | 1500.8 | 242.6 | 553.7 | 1.62E-01 | 3.69E-01 | 3.77E-01 | 8.60E-01 |
| sig_y | nm | 703.8 | 3.0 | 5.0 | 4.26E-03 | 7.04E-03 | 9.93E-03 | 1.64E-02 |
| SigX*SigY | nm^2 | 1056321.0 | 727.6 | 2742.3 | 6.89E-04 | 2.60E-03 | | |
| | | | | | | | | |
| P_b | MW | 0.036 | 6.921 | 11.294 | 190.88 | 311.51 | | |
| I | uA | 0.788 | 27.683 | 45.176 | 35.12 | 57.32 | | |
| I*N | A | 32315.5 | 207619.2 | 903528.0 | 6.42 | 27.96 | | |
| | | | | | | | | |
| L | | 3.04E+30 | 2.03E+34 | 3.44E+34 | 6668.90 | 11308.32 | | |
| CrossSection | nb | 30 | "Free"=Energy, Beam Power, Q/bunch | | | | 34.92 | 151.95 |
| Event Rate | Z/hr | 328 | | | | Disruption | 0.72 | 1.05 |
| | | | | | | Damping Ring | 40.75 | 24.95 |
| | | | | | | Emittance Preservation | 2.10 | 2.38 |
| | | | | | | Aggressive FF | 3.12 | 1.20 |
| | | | | | | Total | 6668.90 | 11308.32 |

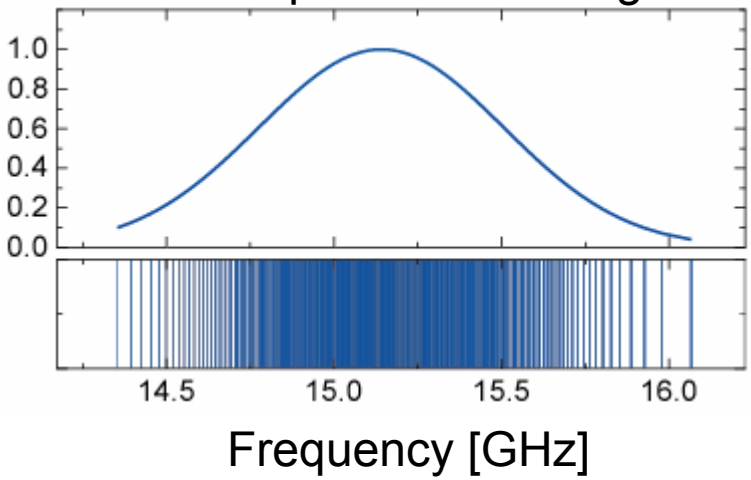
# Bunch Trains

## Accelerator Structure Long-Range Wakefield

- Goal: reduce transverse coupling between bunches to ~0
  - → Alignment and emittance issues are dominated by single bunch
- Requires suppressing the accelerator structure long-range wakefield to <1V/pC/mm/m
  - Detune and damp accelerator structure wakefield
  - Focus of accelerator structure R&D in early 90's

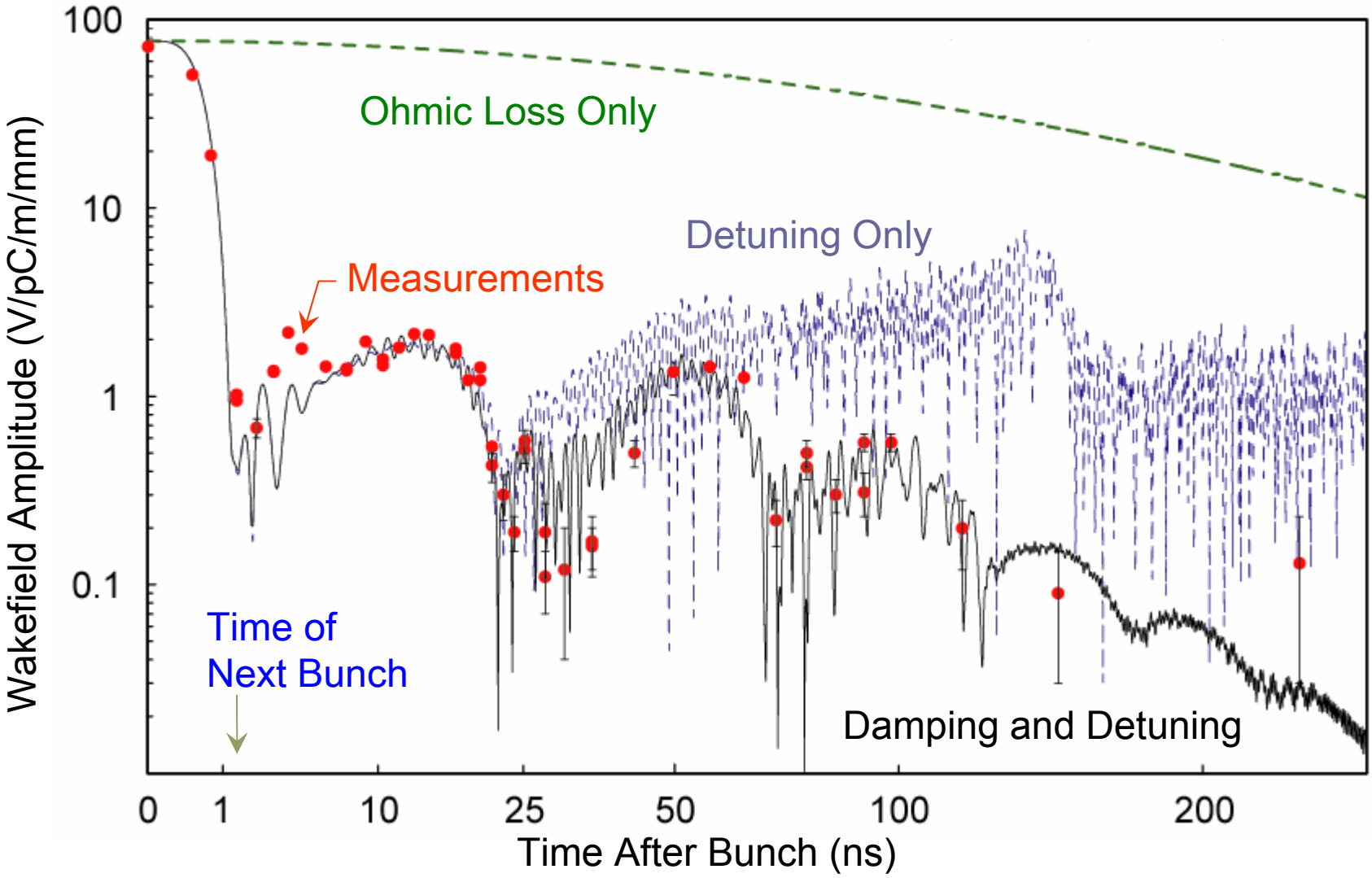
Slots for damping the dipole modes

Cell dipole mode frequencies which provide detuning



# Structure Long-Range Wakefield

## Theory and Measurements



# Bunch Trains
## Long-Range Wakefields Have Small Effect

- Accelerator structure wakefield is suppressed by ~100
  - Use combination of detuning and weak damping
  - Sets requirements on dipole frequency distribution and structure fabrication – discussed by Chris Adolphsen
- Long-range wakefield has minimal effect on bunch train
  - Bunch train behaves like single bunch → alignment tolerances driven by short-range wakefield
- Damping rings: Beam current is smaller than in B-factories
  - Kicker stability is required to keep well aligned bunch train
- Intra-train feedback can remove pulse-to-pulse jitter
  - Demonstrated IP-style feedback with 60~70 ns latency (FONT)
  - Intra-train feedback requires well aligned bunch train

# Peak Luminosity
## ~7,000 times larger than SLC

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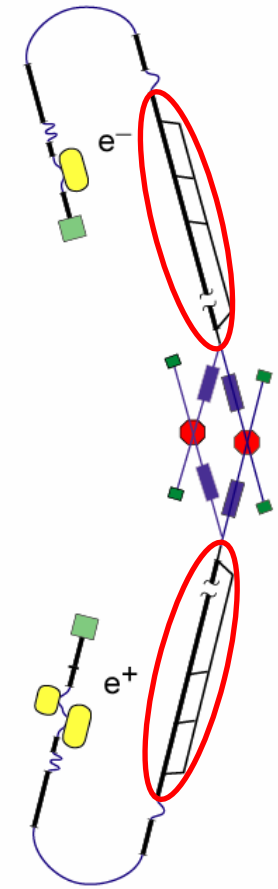


# Emittance Preservation

## Preserve Small Emittances from DR → IP

1. Parameters chosen to make wakefields manageable

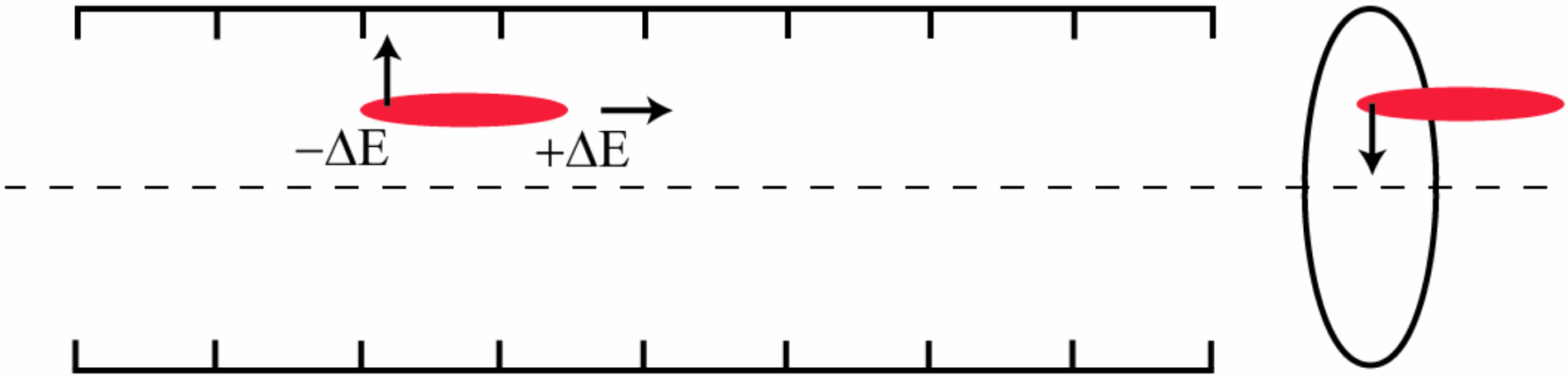
2. Make extensive use of demonstrated BBA techniques
   - Align magnets and structures for complete flexibility
   - Suite of BBA and tuning techniques
   - Necessary instrumentation and controls demonstrated

3. Multiple paths to ensure stable beams for tuning and luminosity

4. Completely modeled transport from DR → IP → Dump
   - Accurately represent operational tuning techniques
   - Generous emittance budgets through system

# Transverse Wakefields
## Wakefields in TESLA are 1000x Smaller

- Transverse wakefields in TESLA are 1000x smaller
  - True but incomplete statement
  - Effect of wakefields depends on charge, bunch length, and focusing
- Real comparison is effect of wakefields on the beam
  - Best quantified with the "BNS autophasing" energy spread $\delta_{Auto}$




Focusing quadrupole overfocuses low energy bunch tail

# Transverse Wakefields

## Already demonstrated NLC wakefield control at FFTB

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  - True but incomplete statement
  - Effect of wakefields depends on charge, bunch length, and focusing
- Real comparison is effect of wakefields on the beam
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| | $\delta_{Auto}$ |
|---|---|
| SLC Design | 9.9% |
| SLC Operation | 5.8% |
| FFTB | 1.1% |
| X-band LC Design | 1.1% |
| TESLA Design | 0.11% |

SLC Design parameters too difficult
→ Operation with lower charge

FFTB operation with still lower charge
→ very stable beam – easy operation

⇒ X-band LC wakefield control already demonstrated at FFTB

# Tolerances

## Lesson from the SLC: Beam-Based Alignment

- All linear collider designs have small $\varepsilon$ → tight tolerances
  - All LC designs require Beam-Based Alignment (BBA)
  - SLC used BBA to align quadrupoles but could not align structures
  - X-band LC will use BBA for both quadrupoles and structures
- Linac tolerances
  - Align quadrupoles BPMs to magnetic center with 5 $\mu$m rms
  - Align the structures to the beam with a 6 $\mu$m rms
  - Align with high performance diagnostics and controls
- Tolerances achievable
  - Required diagnostics and controls demonstrated
  - Multiple BBA techniques demonstrated

# Beam Based Alignment

## All Necessary Techniques have been Demonstrated

X-band uses beam-based techniques to align the magnets and structures

**Yearly**
Conventional methods

**Pre-Alignment**
Install 50 ~100 μm level

**Establish Beam**
Steer to post-linac dump

**Monthly**
Methods from SLC & FFTB
Invasive to Luminosity

**Beam-based alignment**
Determine Q-BPM-to-quad offsets using quad-shunting

**Establish 'Gold' Orbit**
Use DF Steering (if nec.) to find low dispersion orbit

**Hourly**
Methods from SLC & ASSET
Non-invasive to Luminosity

**Steer to Gold Orbit**
Use quad movers to steer

**Align structures to orbit**
Use S-BPMs to center struct.

**Tune Emittance bumps**
Use ε-wires to opt. ε

**Lock Beam-based Fbck.**
Maintain orbit with feedback

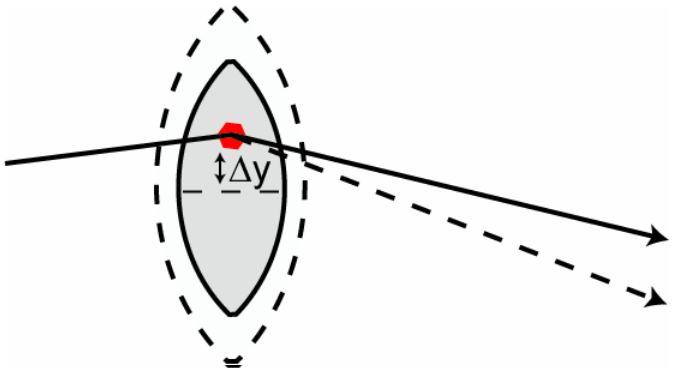
# Quadrupole Beam-Based Alignment

## Utilize Robust, Local Alignment of Magnets

- Multiple quadrupole BBA alignment techniques
  - Quad-shunting (used many places; FFTB demonstrated <7 μm)
  - Dispersion-Free Steering (tested on SLAC linac)
  - Ballistic alignment (tested in SLC S-1 and FFS)
  - Emittance bumps (used routinely in SLC)
- Advantages and disadvantages to each
  - Quad-shunting most robust and most local technique and has demonstrated performance at NLC-level
- X-band LC BBA procedure is based on quad-shunting followed by other techniques to refine solution
  - Dispersion-Free Steering
  - Emittance bumps like those used in the SLC linac

# BBA: Quadrupole Shunting
## Robust, Local Alignment of Magnets

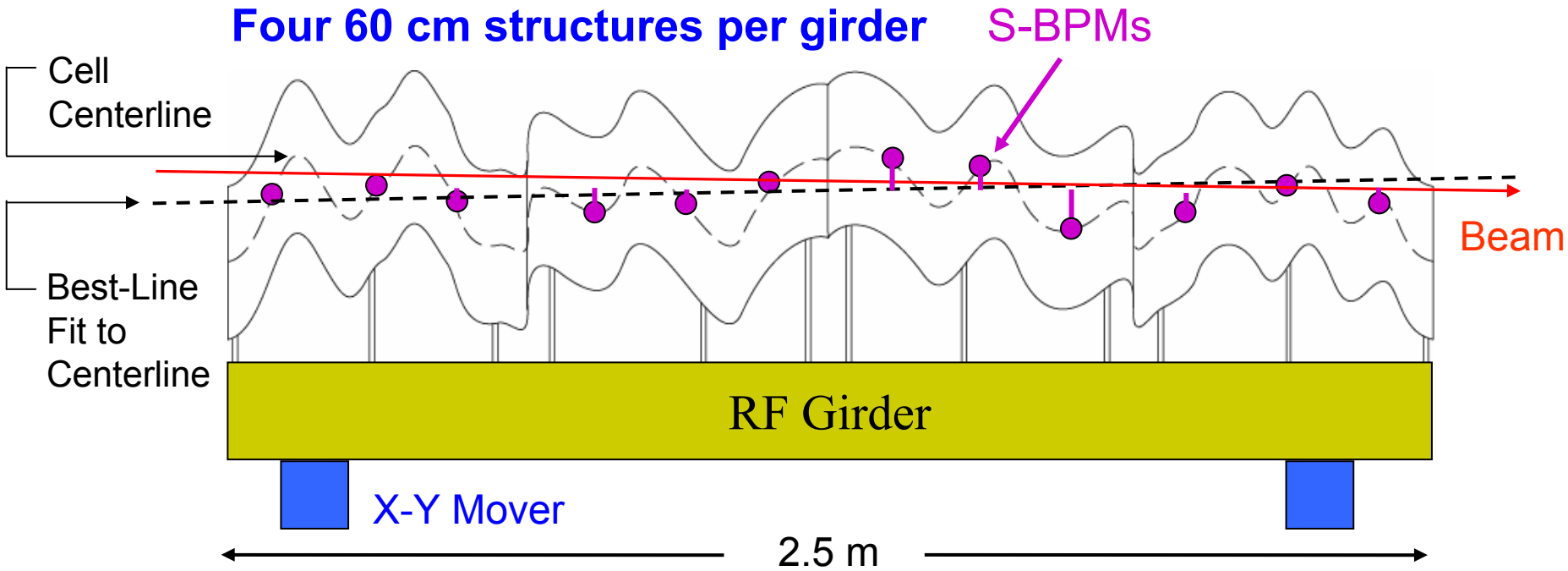
- Quadrupole shunting: find the magnetic center by varying the quad strength and measuring the resulting deflection




- Determine BPM-quad offset
- Nulling meas; good sensitivity
- Main systematic error: magnetic center shift with excitation
- Prototype is measured to be 2~3x better than spec.

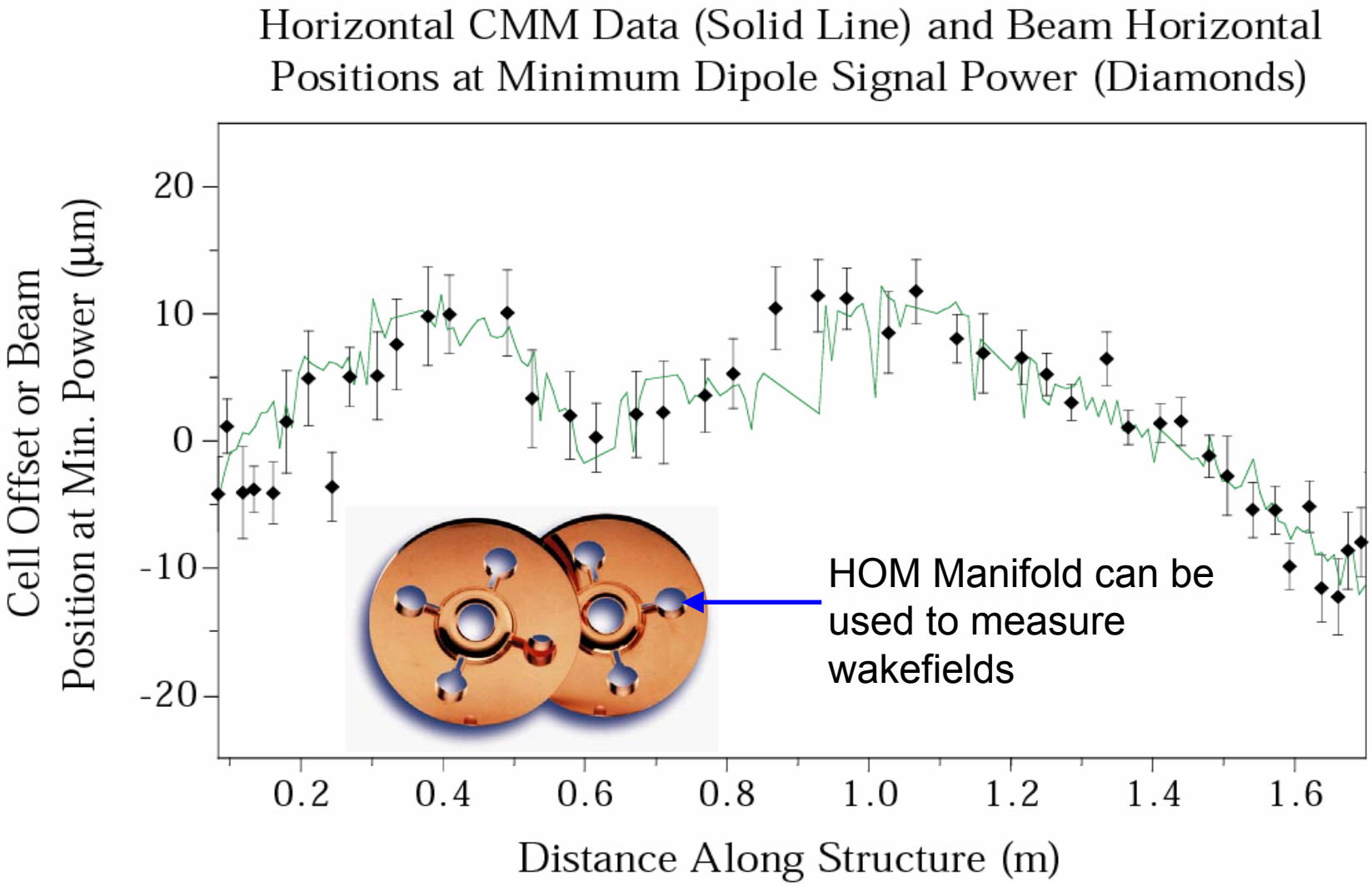
# Structure Straightness and Positioning

## Align Structures to the Beam using Wakefield Signal




1) Before installation, straighten and align structures on rf girder such that deviation of cell centers from best-line fit is 100 μm peak-to-peak
2) During operation, use S-BPM measurements (purple dots) to determine optimal beam trajectory and move girder to the beam with remote movers – want average offset less than 3μm

# Structure BPM
## High Performance Diagnostic

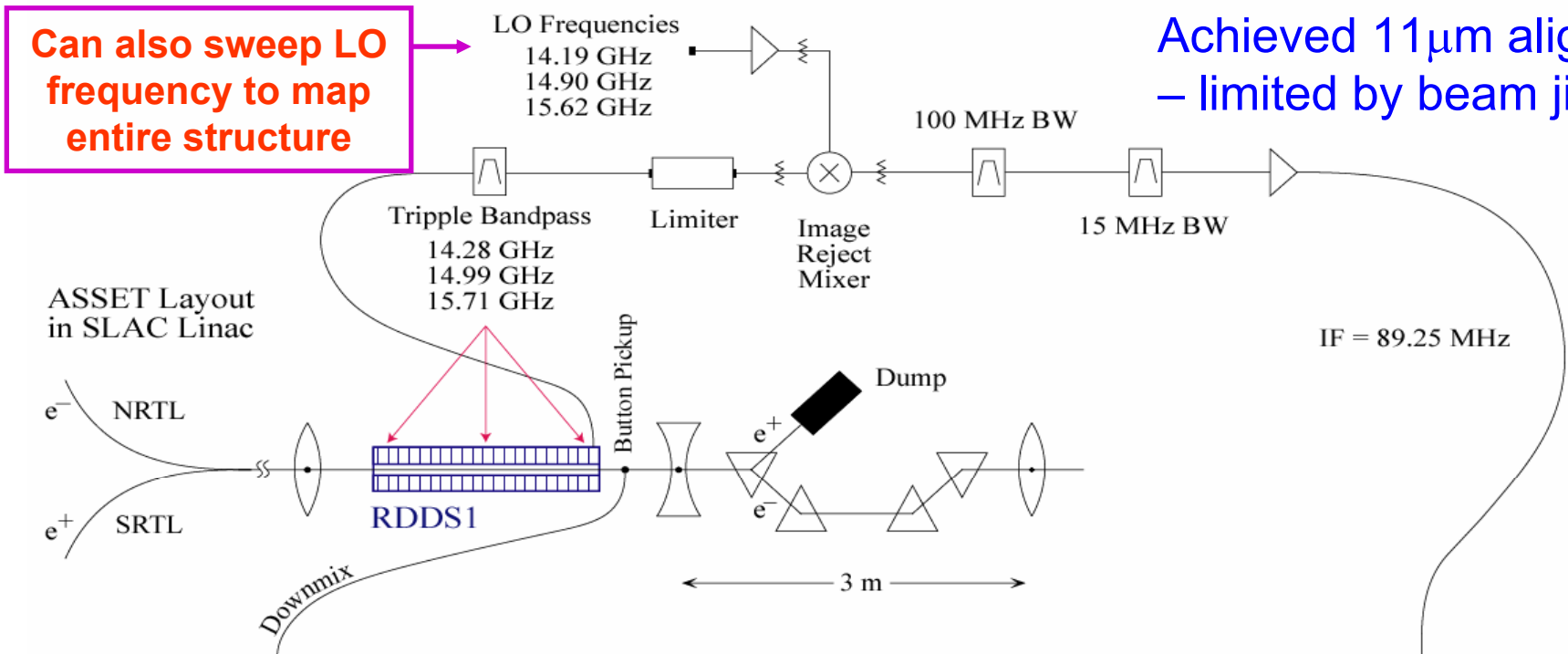


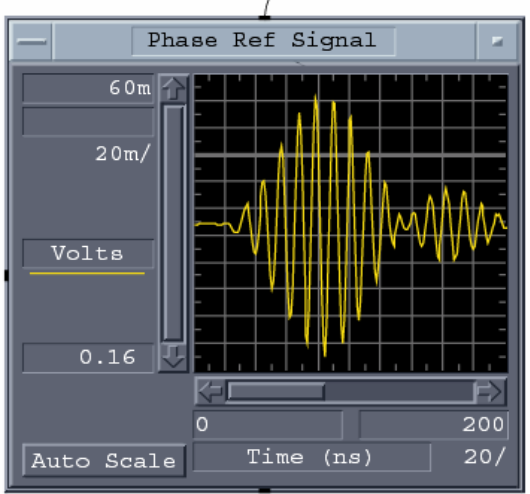
# Test of Structure-BPM in ASSET

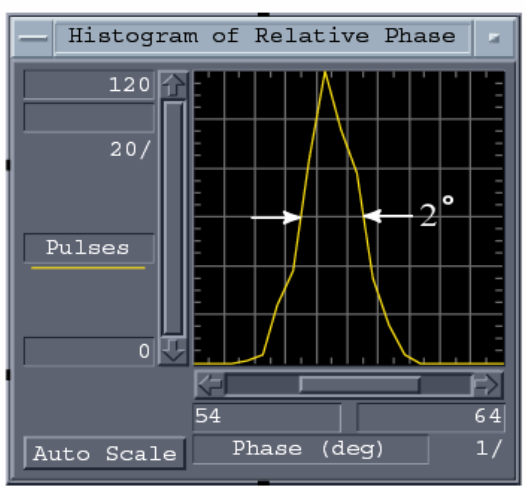
## Demonstration of Alignment Technique

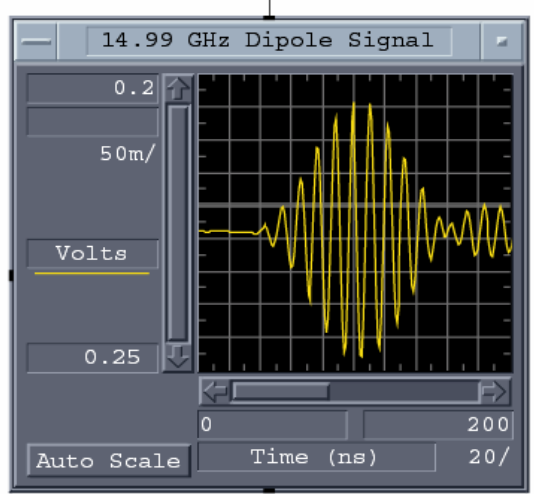
**Can also sweep LO frequency to map entire structure**

Achieved 11μm alignment – limited by beam jitter



# Vibration and Drifts

## Stability is Necessary for Beam Tuning

- Extensive measurements of natural ground motion
- Many measurements of ‘cultural’ sources and transmission
  - Isolated measurements of modulators, accelerator structures with cooling, quadrupole magnets with cooling all look acceptable
  - Transmission between tunnels is large so must be careful in utility tunnel as well as the main tunnel
- Developing prototypes of main linac girder and utility clusters to measure vibration of full system
- Can always use active suppression for further improvement
  - Magnets and supports easily accessed
  - Stabilization systems developed at DESY, CERN, KEK, and SLAC

# IP Stabilization
## Three Approaches

- Three different approaches being pursued:
  1. Quiet site and IR/Detector engineering (many suitable sites identified)
  2. Active (inertial) stabilization
  3. Fast intra-train feedback (FONT at NLCTA and FEATHER at ATF)

- Inertial stabilization
  - Developing compact non-magnetic sensors (in-house and commercial)
  - Stabilizing an extended object that models a PM final quadrupole and cantilevered support tube

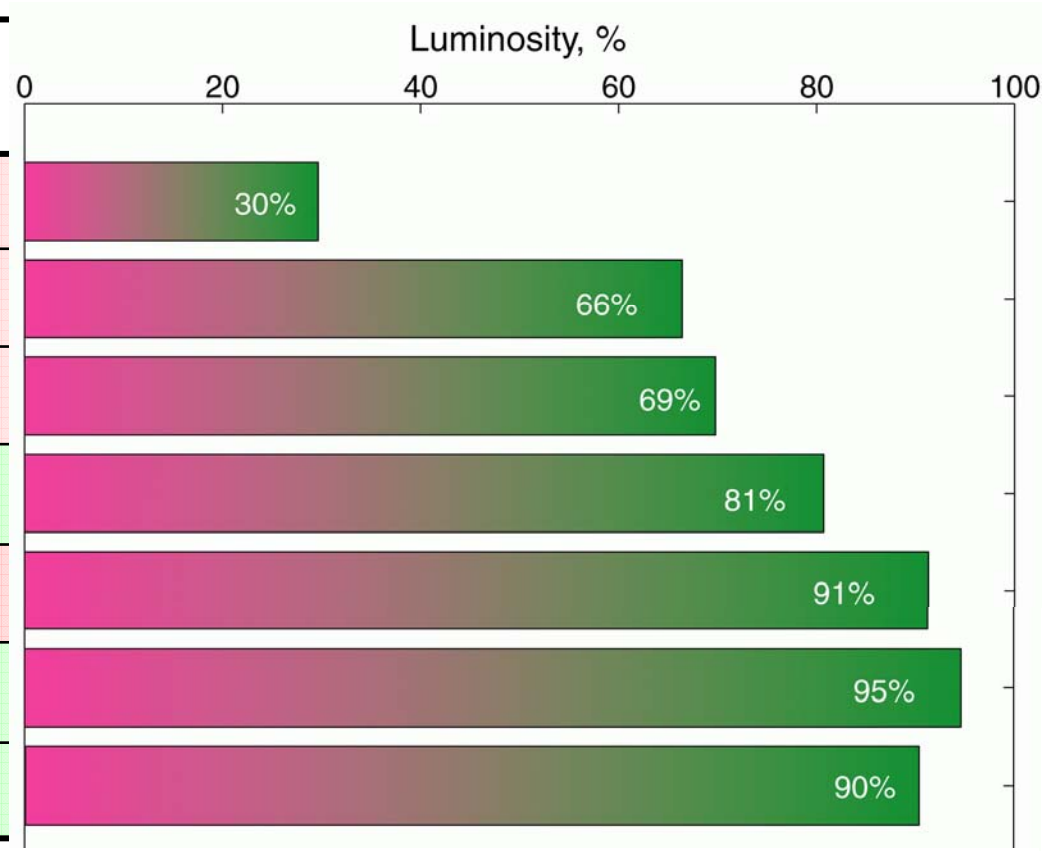
- Feedback On Nanosecond Timescales (FONT) at NLCTA
  - 2003 run demonstrated ~15x reduction of intra-train offsets
  - Latency was about 60 ns $\Rightarrow$ Significant effect on 75% of train

# IP Stabilization Summary

## Multiple Paths to Stabilize Collisions

IP collisions can be stabilized using any two out of the three approaches with >90% of peak luminosity

| Quiet Detector | Active Stabilization | FONT |
|---|---|---|
| 20 nm | No | No |
| 4 nm | No | No |
| ~20 nm* | Yes* | No |
| 20 nm | No | Yes |
| 4 nm | Yes | No |
| 4 nm | No | Yes |
| ~20 nm* | Yes* | Yes* |




* based on measurements in NLCTA. 20 nm vibration measured on SLD.

# Realistic Simulation Studies

## Example: Emittance Bumps

- Emittance bumps are the classic 'global' correction method
  - Emittance bump technique used in SLC operation and TESLA sims.
  - 100% effective if used or studied with a single primary $\Delta\varepsilon$ source
- Performance less optimal in LC with many $\Delta\varepsilon$ sources
  - Techniques in simulation based on SLC operational procedures
  - Alternate approaches may yield better performance but ….

Bumps with combined wakefield and dispersive errors after nominal tuning are 30% effective

| | US Warm $\Delta\varepsilon$ | US Cold $\Delta\varepsilon$ |
|---|---|---|
| Nominal Errors | 25% → 19% | 37% → 21% |

Still useful technique to 'finish' emittance tuning and achieve best performance

# DR → IP Simulations

## Extensive Studies Refined for over 10 Years

- Tools developed and benchmarked against SLC
  - Different codes compared against each other during TRC
  - Reasonable agreement between simulations
- Studied many different techniques and many different effects
  - Complete simulations including 'all' static errors and many dynamic errors while modeling operational tuning procedures
- About 20,000 cpu-hrs in simulations of NLC, TESLA, US Warm, and US Cold over the last two years
- Emittance budgets based on detailed DR → IP simulations
  - Dilution budget has 100% $\Delta\varepsilon_y/\varepsilon_y$ in BC, BDS, and linacs
  - Budget does not assume use of $\varepsilon$-bumps

# Emittance Preservation Summary

## Preserve Small Emittances from DR → IP

1. Parameters chosen to make wakefields manageable

2. Make use of demonstrated BBA techniques
   - Align both magnets and structures for complete flexibility
   - Correct emittance dilution sources locally for stable solution
   - Demonstrated necessary instrumentation and controls
     - Most prototypes are better than spec → see poster

3. Multiple paths to ensure stable beams for tuning and luminosity

4. Completely modeled transport from DR → IP → Dump
   - Accurately represent operational tuning techniques
   - Generous emittance budgets through DR → IP system

# Peak Luminosity
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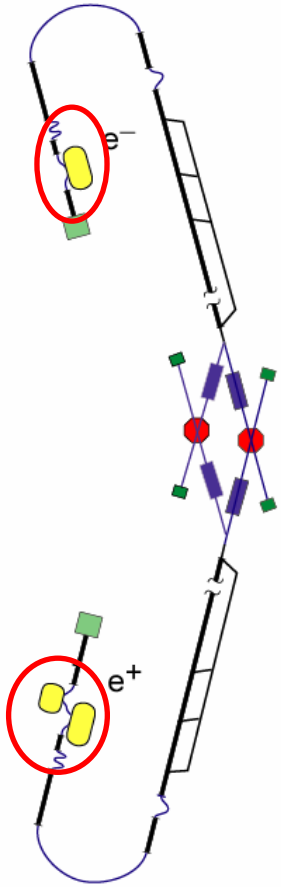


# Emittance Generation

## Damping rings have most accelerator physics in LC

- Required to:
  1. Damp beam emittances and incoming transients
  2. Provide a stable platform for downstream systems
  3. Have excellent availability ~99% (best of 3rd generation SRS)

- Mixed experience with SLC damping rings:
  - Referred to as the "The source of all Evil"
  - Collective instabilities; Dynamic aperture; Stability

- X-band damping ring designs based on KEK ATF, 3rd generation SRS, and high luminosity factories
  - Experimental results provide high confidence in design

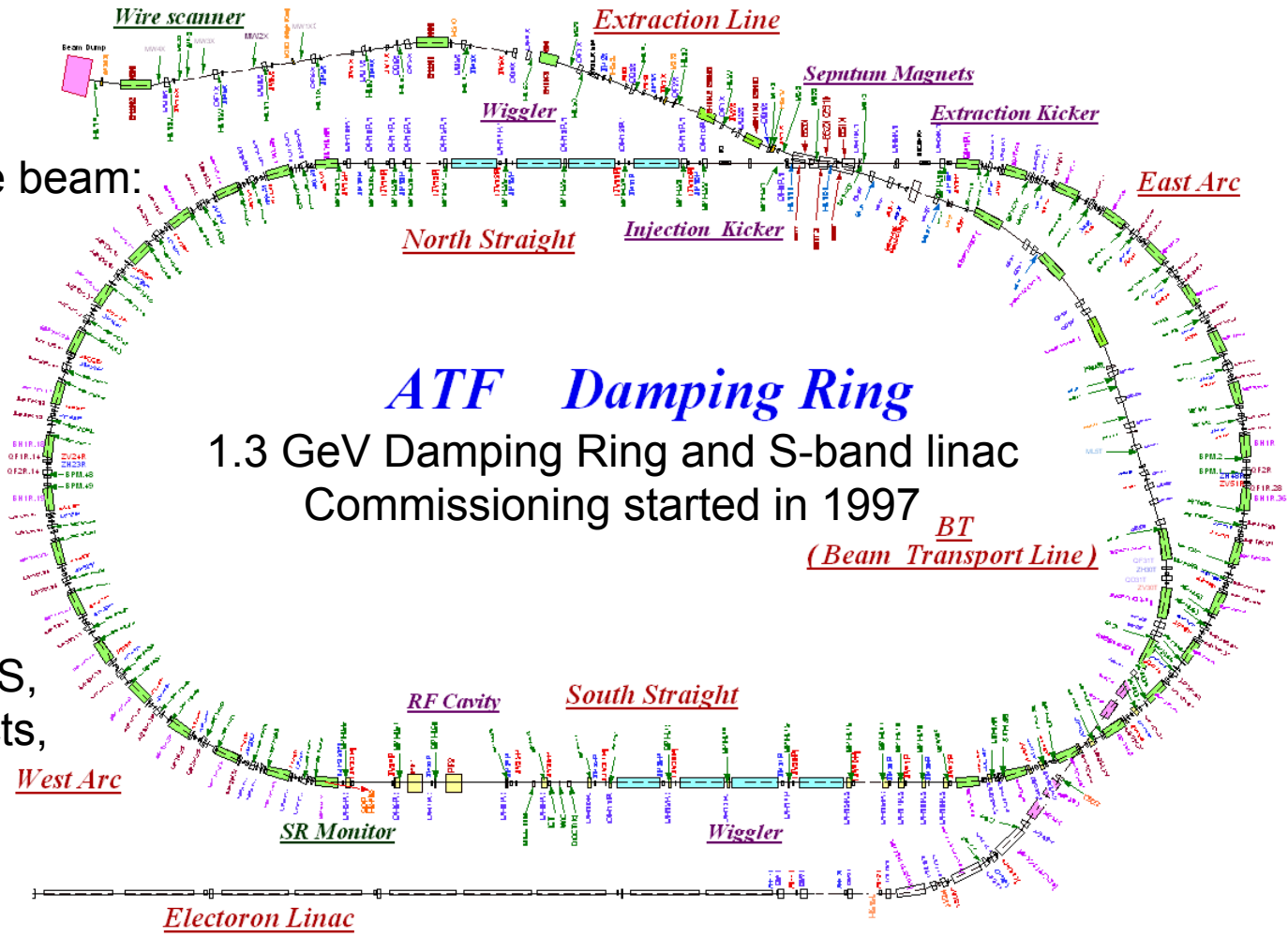
# KEK ATF
## Largest LC Test Facility

World's lowest emittance beam:

- $\varepsilon_y$ = *4 pm-rad* below X-band LC requirements

Used to verify X-band DR concepts

Detailed measurements of emittance tuning, lattice properties, IBS, ions, collective effects, and instrumentation

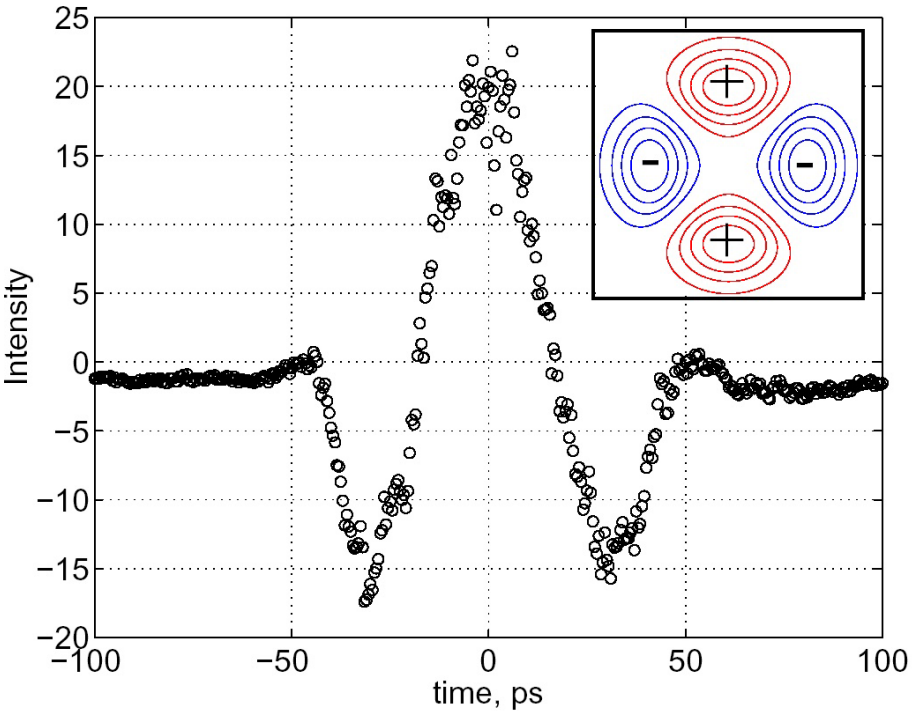


# Collective Instabilities

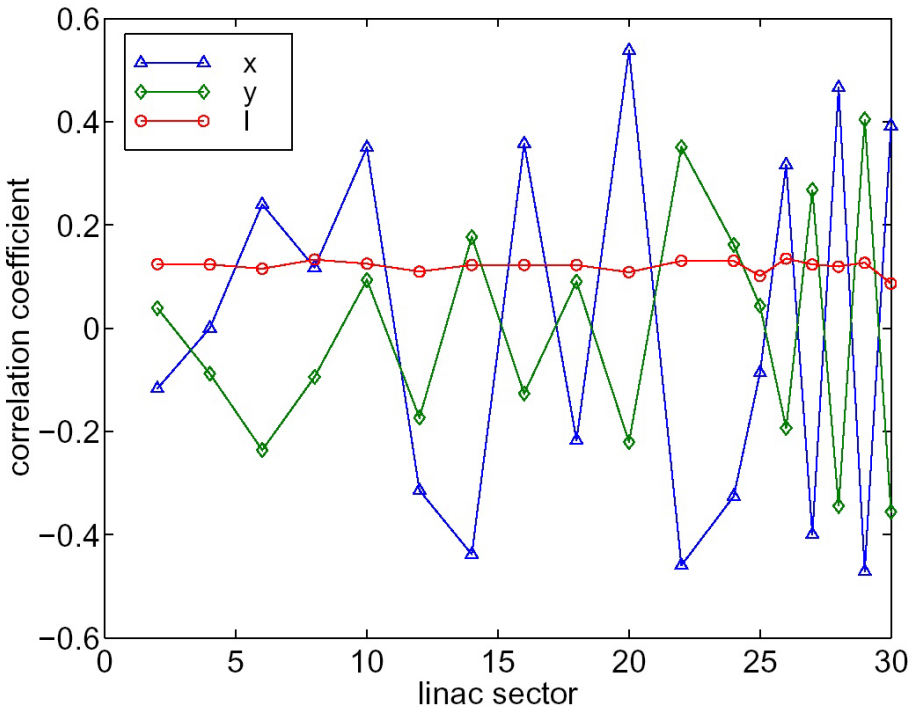
## Downstream Systems Sensitive to Rings

- Example: bursting microwave quadrupole instability in the SLC ring caused μm's of jitter at end of the linac
  - Complicated effect that involved interplay of the instability, damping ring feedback systems and linac beam dynamics

Bursting quadrupole instability in SLC DR redistributed 3% of charge




Correlation between DR instability and linac BPM – 20 μm of motion



# Electron Cloud
## Active R&D Program Aimed at Suppression

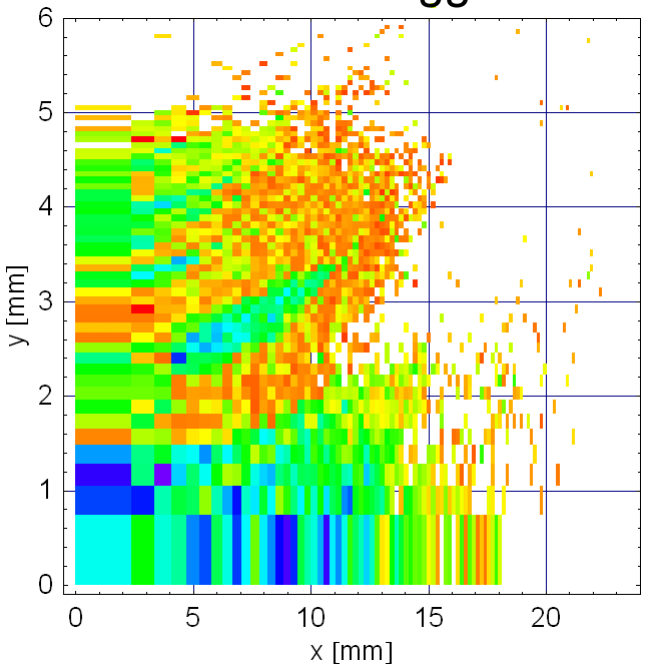
- Electron cloud is a known limitation in PEP-II and KEK-B positron rings
  - Electrons from photo-emission, ionization, or secondary emission are trapped in the potential well of the positron beam
- Thresholds for cloud formation are very similar in both X-band and TESLA damping ring designs
  - Low densities can cause large tune shifts, single, or multi-bunch collective instabilities → Address cloud everywhere in all rings
- Active R&D effort on vacuum surfaces and treatments
  - No single vacuum material sufficient
- Plan to test treated coupons in PEP-II and install treated chamber in ~ 2 years

# Wiggler Nonlinearities

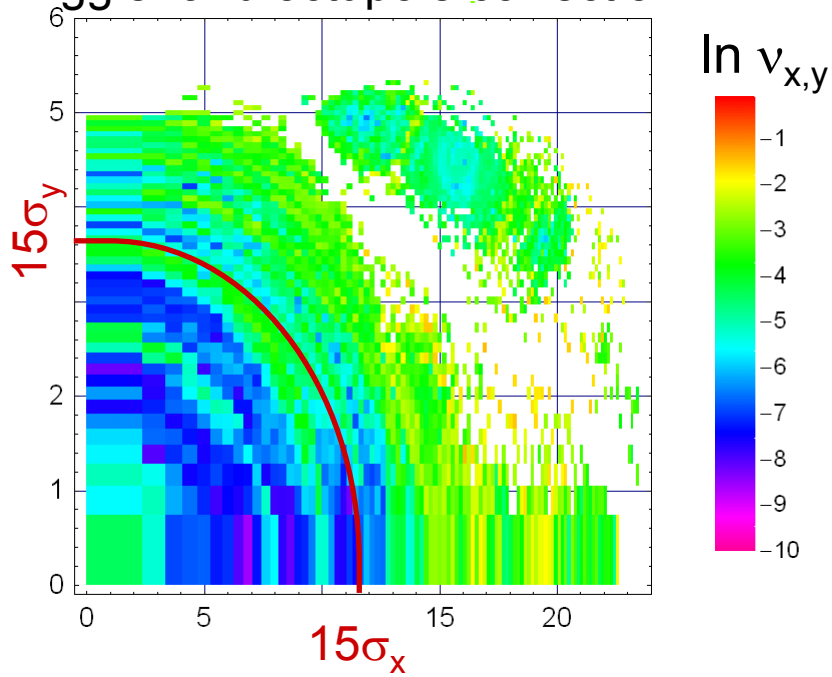
## Ring Designed with $15\sigma_{inj}$ Dynamic Aperture

- X-band damping ring dynamic aperture >15x injected beam
  - High power injector (55 kW) – cannot allow injection losses
  - Detailed modeling of dynamic aperture with wiggler field map

Dynamic aperture with nonlinear wiggler




Dynamic aperture with wiggler and octupole correction



# X-band Damping Rings
## Designed with Care of 3rd Generation SRS

- ✓ ATF and the ALS at Berkeley have demonstrated the specified vertical emittance
- ✓ Tolerance sensitivities require the care of 3rd generation SRS
- ✓ Collective effects are more important than in 3rd generation SRS
- ✓ Nonlinear dynamics enter new regime with long wiggler

| | SLS | ALS | ATF | X-band MDR | TESLA DR |
|---|---|---|---|---|---|
| Circumference [m] | 290 | 200 | 140 | 300 | 17,000 |
| Energy [GeV] | 2.4 | 1.9 | 1.3 | 1.98 | 5 |
| Bunch Charge [$10^{10}$] | 0.5 | 0.6 | 0.9 | 0.75 | 2.0 |
| Emittance x [nm] / y [pm] | 4.8 / 15 | 6 / 5 | 1.2 / 4.5 | 0.61 / 4.9 | 0.8 / 1.4 |
| Sextupole Alignment [μm] | 70 | 30 | 50 | 55 | 10 |
| Quadrupole Rotation [μr] | 370 | 200 | 870 | 500 | 40 |
| Impedance (Z/n) [mΩ] | 200 | 80 | 600 | <600 | <60 |
| Wiggler length [m] | 18 | 30 | 0 | 62 | 432 |

# Emittance Generation Summary

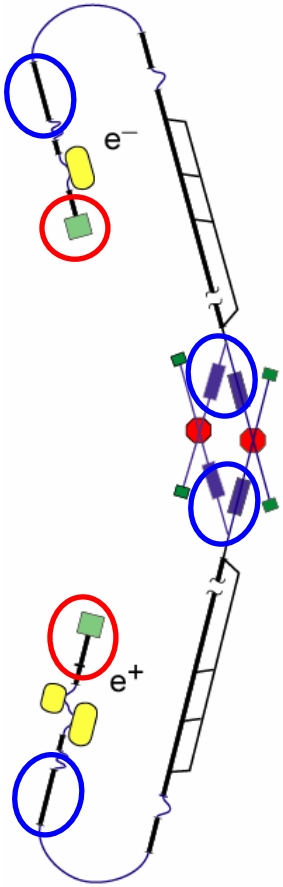
## KEK ATF is a full scale prototype for the X-band DR

- Demonstrated at ATF:
  - X-band DR alignment tolerances and emittance generation
  - X-band DR kicker rise/fall times and required stability
  - Single bunch collective effects in desired regime for X-band DR
  - Required instrumentation for LC
- Demonstrated at luminosity factories:
  - High current multi-bunch operation (B-factories)
  - Dynamic aperture with large wigglers (CESR-C)
- Outstanding:
  - Ongoing studies on electron cloud and ion instabilities for all LC damping rings
- To ensure stability and availability future damping rings will require engineering like 3rd generation light sources

# Peak Luminosity
## ~7,000 times larger than SLC

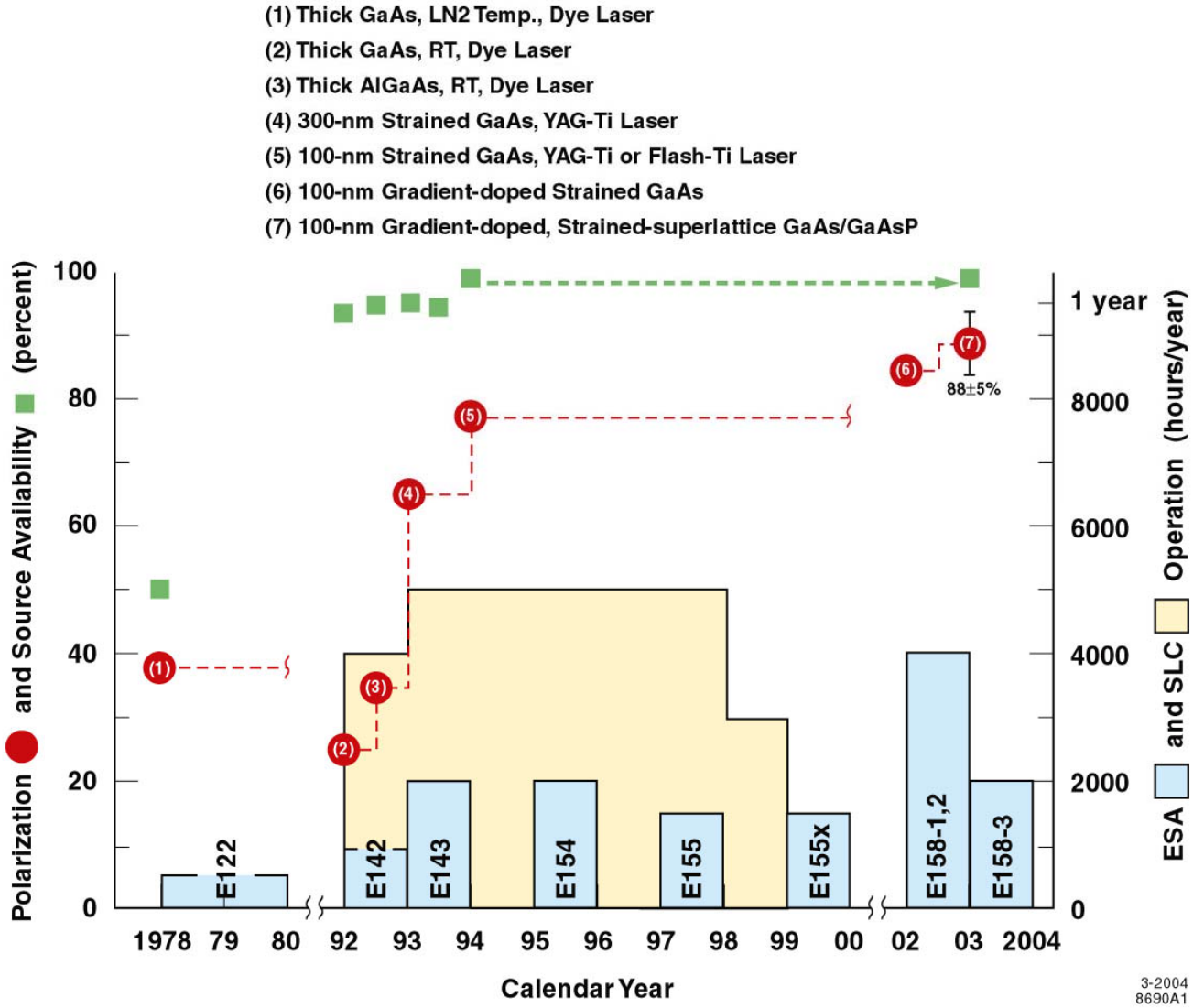
$$L = \frac{f_{rep}}{4\pi}\frac{n_b N^2}{\sigma_x \sigma_y} H_D \quad \Rightarrow \quad L = \frac{P_b N}{4\pi mc^2}\frac{H_D}{(\beta_x \beta_y)^{1/2}(\gamma\varepsilon_x \gamma\varepsilon_y)^{1/2}}$$

- Focusing $(\beta_x * \beta_y)^{-1/2}$ NLC/SLC → 3
  - ✓ Demonstrated at FFTB
- Disruption $H_D$ NLC/SLC → 0.7
  - ✓ Demonstrated at SLC
- Emittance $(\gamma\varepsilon_x * \gamma\varepsilon_y)^{-1/2}$ NLC/SLC → 85
  - ✓ Low Emittance Transport and Damping rings
- Beam power term $(P_b * N)$ NLC/SLC → 35
  - ✓ Bunch trains, Particle sources, Collimation and MPS



# Polarized Electron Source

## Based on Cathode R&D for SLC and E-158



# Positron Source Configuration
## Independent Positron Source

- SLC Positron source used 30 GeV electron beam from shared electron linac
- Three operational problems:
  1. Difficult to commission and develop
     - Unable to commission or perform machine development on positron system without tuned 30 GeV electrons
  2. Low yield
     - Factor of 2 in yield lost due to apertures
     - Could not recover by increasing electron beam current
  3. Coupled system sensitive to cross talk
     - Fluctuations in either the electron or positron current would couple into other beam
- Design positron source with independent drive e- beam

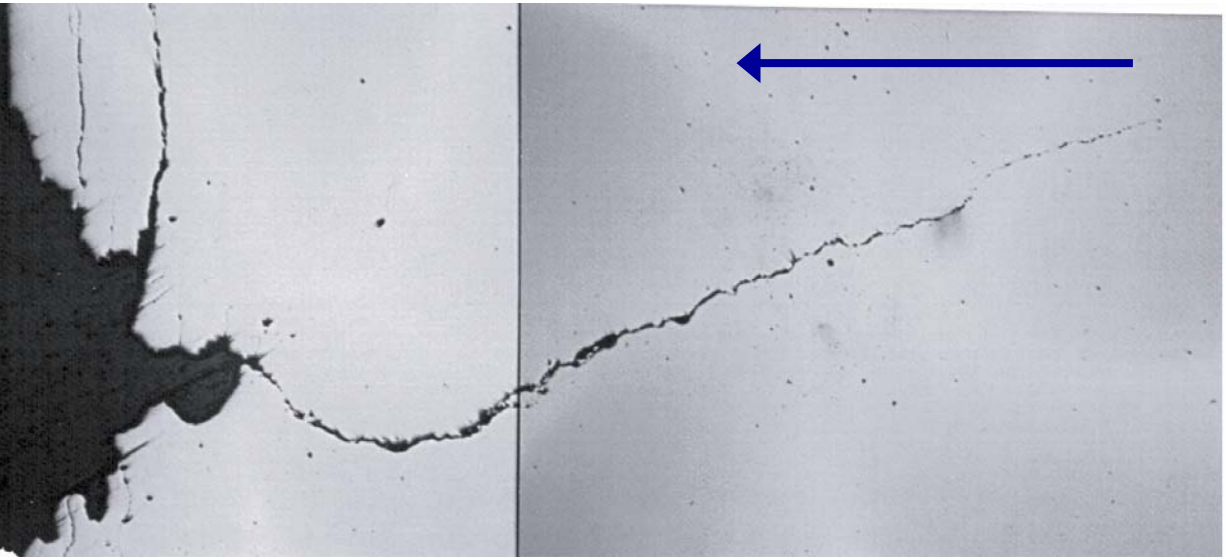
# Positron Source Target

## Design is Based on SLC Experience with *WRe*

- SLC e+ target failed after 5 years at stress levels ~2x lower than previously measured and predicted for *WRe* targets

SLC e+ target

Beam direction



- SLC target studied at LANL and modeled at LLNL
- Problem due to embrittlement from radiation damage
- NLC source is based on multiple targets to reduce stress

- Radiation damage problem is thought worse for the *Ti* targets planned for undulator based sources

# Positron Target Options

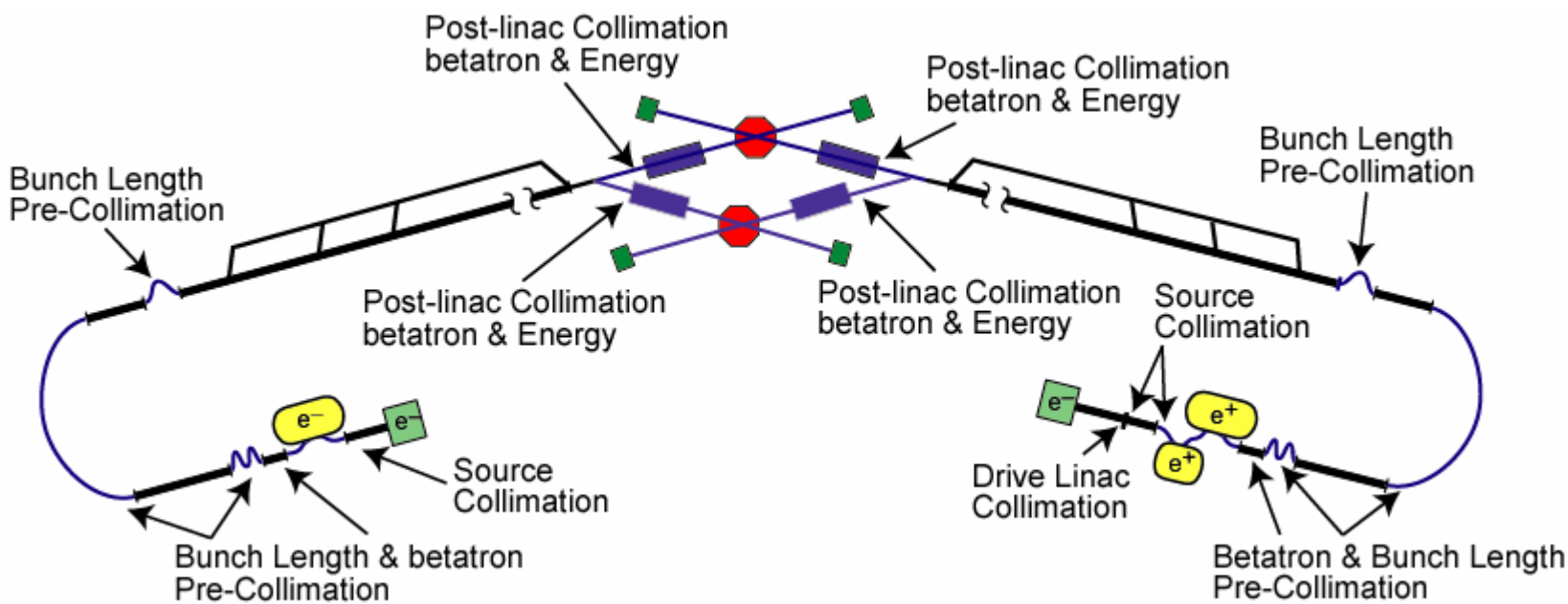
Conventional target is not more difficult than undulator target

| | NC Conv. | NC Und. | SC Conv. | SC Und. |
|---|---|---|---|---|
| E beam [GeV] | 6.2 | 153 | 6.2 | 153 |
| Ne-/bunch [1e10] | 0.75 | 0.75 | 2.00 | 2.00 |
| Undulator Len. [m] | - | 150 | - | 150 |
| Energy/pulse [J] | 477 | 1130 | 28000 | 44300 |
| Target Mat. | WRe | Ti | WRe | Ti |
| Target Thick. [rl] | 4 | 0.4 | 4 | 0.4 |
| Absorption | 14.0% | 8.6% | 14.0% | 8.6% |
| Spot size [mm] | 1.6 | 0.75 | 2.5 | 0.75 |
| # targets/spares | 3 / 1 | 1 / 1 | 2 / 1 | 1 / 1 |
| Target radius [m] | 0.125 | 0.125 | 0.8 | 0.8 |
| Rotation [rpm] | 46 | 46 | 1500 | 1200 |
| $\Delta$T [C] | 189 | 422 | 256 | 410 |
| Yield | 1.5 | 1.5 | 1.5 | 1.5 |

# Beam Collimation

## SLC Luminosity was Frequently Background Limited

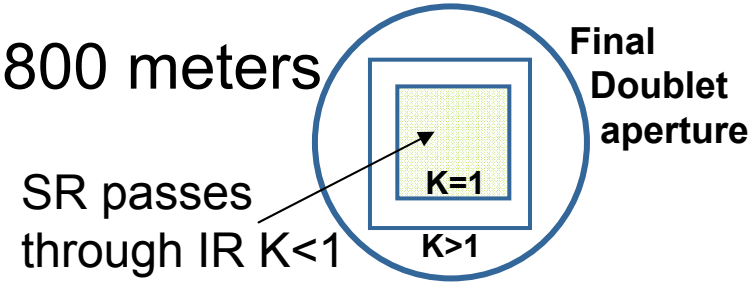
- Collimation system is integral to design and is part of Machine Protection System
  - Collimation system designed for beam tails 1000x that expected
  - Passive energy collimation and consumable betatron collimation
  - Many advantages over SLC
    - No synchrotron radiation in IR
    - Beam tails from damping rings collimated at low energy



# Beam Collimation

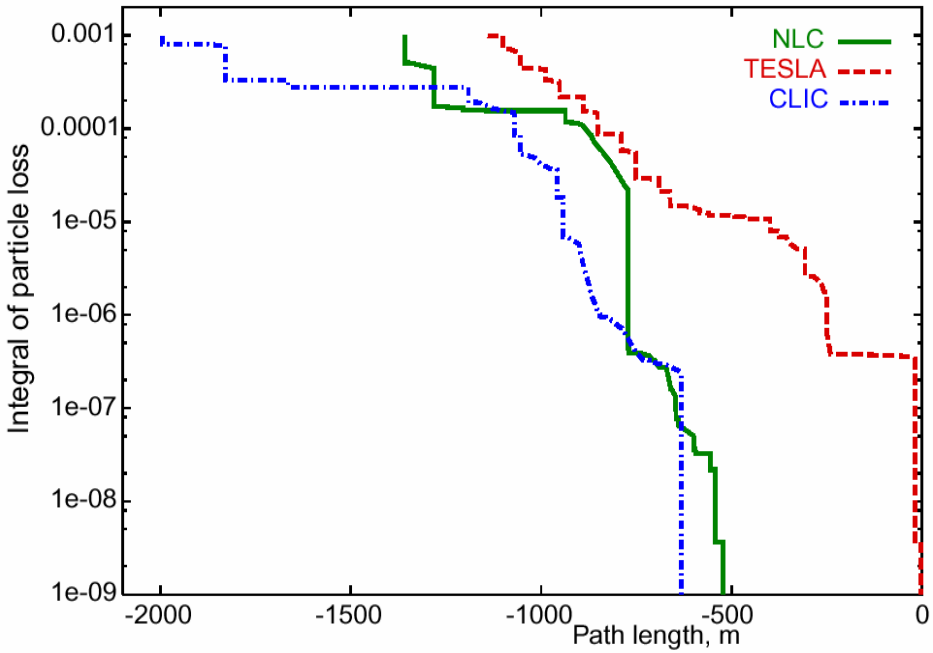
## TRC Task-force Reviewed Basic Design

- Excellent performance in length of 800 meters
  - All tail particles removed 500 meters upstream of IP

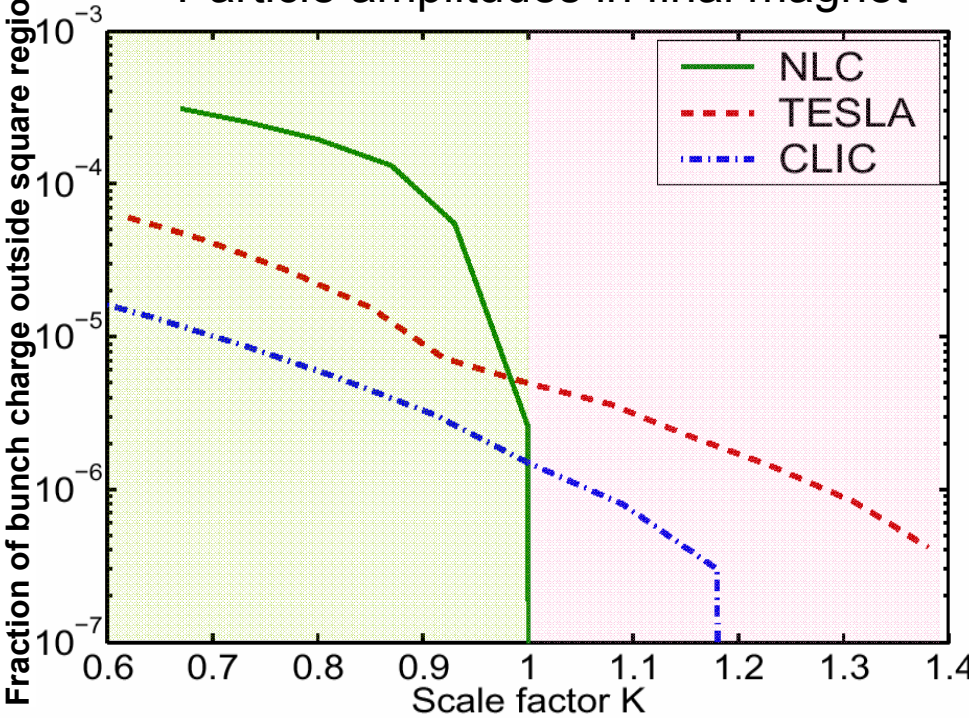



Tails versus s from IP

NLC BDS starts at s = -1300 meters




Particle amplitudes in final magnet



# Beam Collimation

## Octupoles Ease Collimator Wakefields

- Collimator wakefields measured in SLAC test facility
  - Measured collimators with Cu and Ti (and C from DESY)
  - OK at 250 GeV but impact low E luminosity

Collimator wakefield jitter amplification from TRC Study $\Delta y = y_0 \sqrt{1 + A_y^2}$

$A_y \propto 1/\gamma$

| | TESLA | NLC | CLIC |
|---|---|---|---|
| δ spoilers | 0.054 | 0.045 | 0.16 |
| δ absorbers | 0.034 | 0.016 | 0.37 |
| β spoilers | 0.55 | 0.59 | 1.67 |
| β absorbers | 0.51 | 0.014 | 0.33 |
| FF spoilers | 0.73 | -- | 0.32 |
| FF absorbers | 0.38 | 0.53 | -- |
| Total $A_y$ | 2.26 | 1.20 | 2.84 |

- Octupole tail-folding opens gaps reducing $A_y$

# Peak Luminosity Summary

- Low Emittance Transport
  - Parameters chosen to make wakefields manageable
  - Extensive use of demonstrated BBA techniques
  - Multiple paths to ensure stable beams for tuning and luminosity
  - Completely modeled transport from DR → IP → Dump
- Damping rings
  - Performance demonstrated at ATF and 3rd generation SRS
- Beam power
  - Long-range wakefields and coupled bunch instabilities not limitations
  - Particle sources based on SLC experience
  - Robust collimation design

# Design Headroom

## Faster Commissioning and Higher Luminosity

- Most sub-systems have substantial headroom
  - For example: $E^-$ Source emittance – Simulations predict $\gamma\varepsilon$ half of design spec $\gamma\varepsilon=10\times10^{-5}$; DR acceptance and damping for $\gamma\varepsilon=15\times10^{-5}$

| | | |
|---|---|---|
| Sources | 50% | beam power |
| | 3x | emittance (described above) |
| | 10x | damping (injected beam 10% of extracted) |
| | 20% | bunch length ($\sigma_z$ > 90$\mu$m; spec=110$\mu$m) |
| RF system | 10% | energy (allocation for trips, phasing, repair) |
| Dilutions | 100% | vertical emittance |
| | 4x | horizontal IP beta function |

- Provide stable operation and flexibility to optimize luminosity
  - Fast commissioning and higher luminosity with time

# Potential for Luminosity Upgrades

- Design margins allow parameter optimization
  - Example 1: if low emittance transport component specs are met $\Rightarrow \Delta\varepsilon_y < 50\%$ and $L = 3\text{x}10^{34}$
  - Example 2: if damping ring alignment can attain and maintain the TESLA DR specs $\Rightarrow \gamma\varepsilon_y << 1\text{x}10^{-8}$ and $L = 4.5\text{x}10^{34}$
- What are the limits? Disruption $D_y$ and beamstrahlung $\delta_B$

$$L \propto \frac{P_{beam}}{E_{cms}} \frac{D_y}{\sigma_z} H_D \qquad \delta_B \propto D_y^2 \sigma_y^2 \left( \frac{\gamma}{\sigma_z} \right)^3$$

  - $L = 4.5\text{x}10^{34}$ assumes $\sigma_z$=110μm and TESLA disruption: $D_y \sim 25$
  - Compress to $\sigma_z$=90μm $\Rightarrow L = 5.5\text{x}10^{34}$ (same $\delta_B$)
  - Assume TESLA-style 1st compression stage of 20x $\Rightarrow \sigma_z$=50μm and $L = 11.5\text{x}10^{34}$ with 2x larger $\delta_B$

# Summary

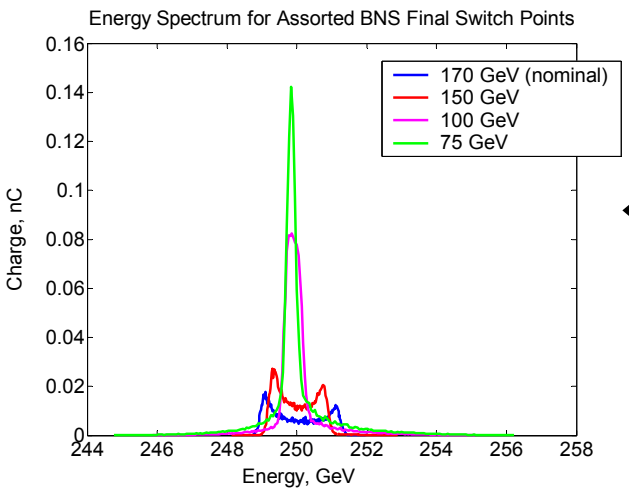
- The X-band design is based on:
  - 20 years of linear collider development including:
    SLC, NLCTA, ASSET, CollWake, ATF, FFTB, Stabilization, …
  - Extensive beam tuning experience with SLC, FFTB, and ATF
  - Proven principles of structure wakefield suppression and S-BPMs
- The design luminosity is possible because:
  - Luminosity performance has been a focus of the design and R&D
    - Performance goals verified with in depth DR → IP simulations
    - Results from prototype testing support the performance goals
    - Essential experience from SLC, FFTB, and ATF included
  - Headroom in design → ensure luminosity goals are attained quickly
- X-band LC is the LC design which has been studied in depth

# Extra Slides

# Energy Spectrum

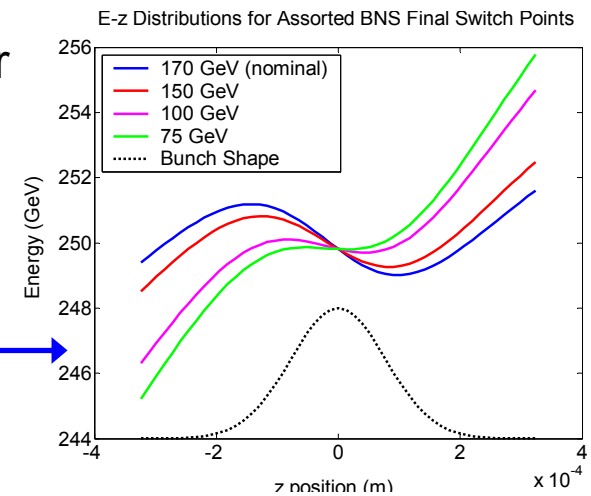
## Narrow Energy Spectrum for Special Measurements

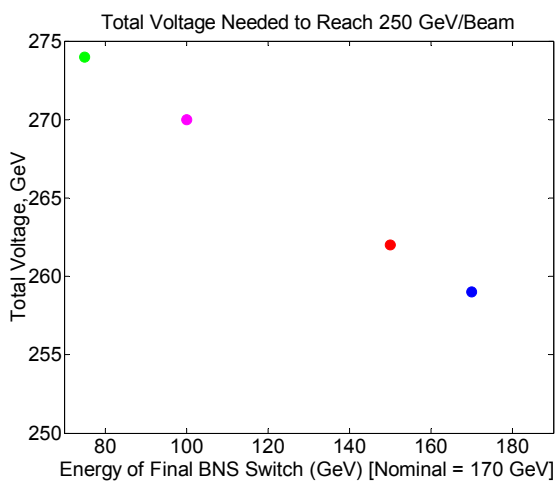
### Adjusting BNS phases allows control of energy spectra




Energy spectrum for different BNS configurations

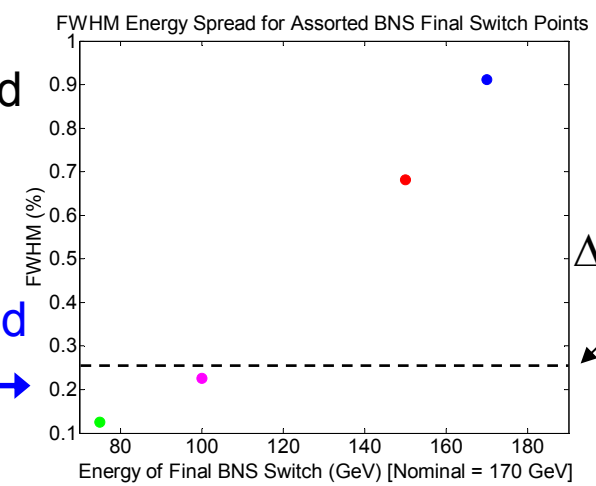
Longitudinal phase space for different BNS configurations




Total voltage required for different BNS configurations

FWHM energy spread for different BNS configurations

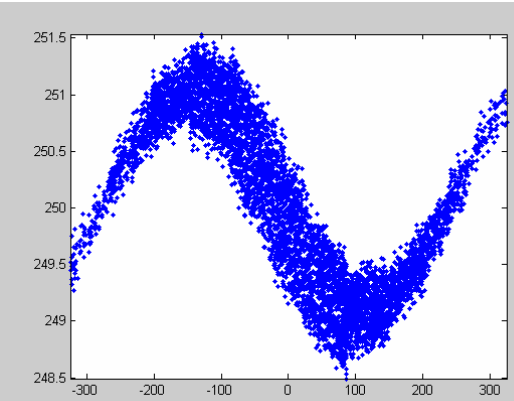



TESLA $\Delta E/E_{FWHM}$

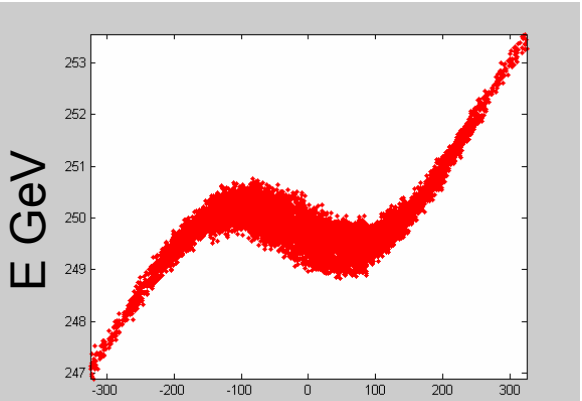
# Energy Spectrum
## Luminosity Energy Bias → 0

- New BNS configuration has small $E_{bias}$

Nominal spectrum



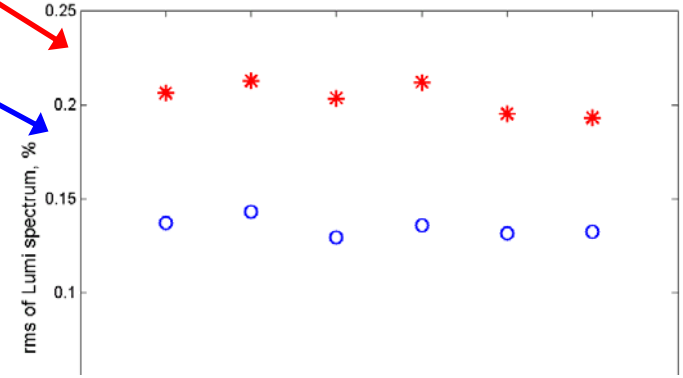

Low $E_{bias}$ spectrum




Luminosity rms spectrum

Nominal

Low $E_{bias}$




Luminosity energy bias

Nominal

Low $E_{bias}$