Laser-Compton Spot Size Monitor (ref 1, 2)

Tsumoru SHINTAKE
KEK: National Laboratory for High Energy Physics

A reliable transverse spot size monitor system for nano-meter beam at collision point in e⁺e⁻ linear colliders.

Laser Interferometer + Compton Scattering + γ-ray detector
Spatial modulation in γ-ray flux.
----> Electron Spot Size

FEATURES

1. Reliable. Simple operation mechanism. Spot Size is Simple function.

2. No high beam power problems. No beam space-charge problems.

3. Ultra-small spot size measurement is possible. Well sensitive to 10 nm with 4th radiation of YAG-laser (266nm).

4. Emittance measurement.
   Divergence σ' from γ-ray profile.
   Phase space (σ, σ') ---> Emittance.

References
Twin-beam
Interference Fringes
(He-Ne Laser)
Young's Configuration

Laser Beam Interference

Interference Pattern (Photon flux)

\[ \frac{\lambda}{\theta} \]
Fig. 4 Variation of the γ-ray number by scanning the beam in vertical direction.
The electron beam size is known by measuring the modulation depth: $\Delta N/N_0$. 
Operation Modes
of Laser-Compton Spot Size Monitor
### Table - 2

<table>
<thead>
<tr>
<th>Laser</th>
<th>Nd : YAG - laser</th>
<th>CO₂-laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonics</td>
<td>4th</td>
<td>2nd</td>
</tr>
<tr>
<td>Laser photon energy in electron rest frame $\varepsilon_1 = \gamma \nu_0 / m_0 c^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(50 GeV)</td>
<td>0.69</td>
<td>0.45</td>
</tr>
<tr>
<td>(500 GeV)</td>
<td>8.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Compton scattering cross-section $\sigma_c / \sigma_0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(50 GeV)</td>
<td>0.45</td>
<td>0.58</td>
</tr>
<tr>
<td>(500 GeV)</td>
<td>0.13</td>
<td>0.20</td>
</tr>
<tr>
<td>$\gamma$-ray energy (maximum) $\nu_{\text{max}} = 2E / (1 + 2\varepsilon)$ (Gev)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(50 GeV)</td>
<td>32 GeV</td>
<td>23.7</td>
</tr>
<tr>
<td>(500 GeV)</td>
<td>473</td>
<td>450</td>
</tr>
<tr>
<td>Required laser power for 1000 $\gamma$-rays/bunch $P_L$ (MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(50 GeV)</td>
<td>57 MW</td>
<td>22</td>
</tr>
<tr>
<td>(500 GeV)</td>
<td>200</td>
<td>64</td>
</tr>
</tbody>
</table>

$$W = 10\, \text{ns} \times 9\, \text{MW} = 90\, \text{mJ} / \text{beam}$$

$\sim \frac{1000 \gamma\text{-rays}}{100\, \text{mJ}} / 10^9 \text{electrons}$.  

Laser
Gamma-ray Energy Spectrum

Electron beam energy: 50 GeV

Cross-section

Gamma-ray Energy (GeV) (a)

Electron beam energy: 500 GeV

Cross-section

Gamma-ray Energy (GeV) (b)
Table 1. Required Specifications of Laser System for Laser-Compton Beam Size Monitor

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1.064 μm, Nd:YAG-laser</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>400 mJ/pulse</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>7 - 10 nsec FWHM</td>
</tr>
<tr>
<td>Energy Stability</td>
<td>&lt; 1 % (for 95% of pulses)</td>
</tr>
<tr>
<td>Pulse Rate</td>
<td>10 pps (range 2 - 20)</td>
</tr>
<tr>
<td>Beam Divergence</td>
<td>&lt; 0.5 mrad</td>
</tr>
<tr>
<td>Beam Pointing Stability</td>
<td></td>
</tr>
<tr>
<td>shot-to-shot</td>
<td>&lt; 10 μrad (deviation from mean axis)</td>
</tr>
<tr>
<td>long term</td>
<td>&lt; 100 μrad/hour</td>
</tr>
<tr>
<td>Spatial Mode</td>
<td>Uniphase</td>
</tr>
<tr>
<td>Spatial Beam Profile</td>
<td>Maximum deviation from Gaussian fit &lt; 15 % at 2 m</td>
</tr>
<tr>
<td></td>
<td>Roundness &gt; 90 %</td>
</tr>
<tr>
<td>Output Pulse Time Jitter</td>
<td>&lt; 1 nsec</td>
</tr>
<tr>
<td>Line Width</td>
<td>&lt; 0.003 cm⁻¹</td>
</tr>
<tr>
<td>Option</td>
<td>Injection Seeding Laser</td>
</tr>
</tbody>
</table>
Quanta-Ray® GCR
Nd:YAG Laser Series

Uniform spatial and smooth temporal profiles and narrow linewidth boost the accuracy and repeatability of your results.

Quanta-Ray pulsed Nd:YAG lasers employ a new optical resonator—the Gaussian coupled resonator (GCR)—to produce spatially uniform high-energy pulses in a single transverse mode. Optional injection seeding produces temporally smooth pulses of nearly transform-limited linewidth. Such high optical quality improves the efficiency of harmonic and other nonlinear conversions and enhances the reproducibility and accuracy of experimental results.

The GCR preserves the advantages of the proven Quanta-Ray resonator—a simple linear layout of oscillator and amplifier stages that is synonymous with excellent beam pointing stability and resistance to optical damage. Consequently, you can expect the GCR to be as dependable as its diffraction-coupled predecessors, but with performance improvements that place it at the top of its class. All things considered, that makes the GCR the first choice among pulsed Nd:YAG lasers.
te harmonics in the output of the designed for mounting conver in separating various harmonic

Model 6300 Injection Seeding Laser

Injects laser light into the cavity of the GCR, so the pulse builds from a single-frequency seed. Injection seeding produces the ultimate in spectral resolution, a nearly transform-limited linewidth of 0.003 cm$^{-1}$. 

Cohesion...
Spatial Beam Profile

Spatial beam profile of a GCR-4-30 taken at 2m from the laser's output coupler. The lasing wavelength was 1064nm.

Near field profile

YAG-rod.

R: Smaller
Spatial beam profile of a GCR-4-30 taken at the focal point of a meneiscus lens.
Propagation of Beam Pointing Error

\[ \theta_f = 4 \theta_i \]

\[ \theta_i = 25 \text{ mrad} \]

Measurement 0.8%
Fig. 7 Imperfectly overlapped laser beam spots.
Misalignment Error

1. Beam Center Offset.

\[ A_0 e^{j\omega t} \exp\left(-\frac{r^2}{w_0^2}\right) \]

Visibility > 95%  
\[ |\Delta x| < 32 \mu m. \]

\[ \theta, < 40 \mu rad. \]

Case 1

Important.

Peak Phase \( E_0 = E_1 + E_2 = A_0 \left\{ \exp \left( -\frac{(x-\frac{\Delta x}{2})^2}{w_0^2} \right) + \exp \left( -\frac{(x+\frac{\Delta x}{2})^2}{w_0^2} \right) \right\} \)

Minimum Phase \( E_0 = E_1 - E_2 = A_0 \left\{ \exp \left( -\frac{(x-\frac{\Delta x}{2})^2}{w_0^2} \right) - \exp \left( -\frac{(x+\frac{\Delta x}{2})^2}{w_0^2} \right) \right\} \)
**GCR Pulsed Nd:YAG Laser**

A GCR pulsed Nd:YAG laser consists of a head and a power supply. The options include:

- **GCR-X-XX**
  - 10 pps version
  - 30 pps version
  - 3: standard output energies
  - 4: higher output energies

**Options**

**Harmonic Generator HG-XX**

- A: SHG Type II KD*P crystal
- B: SHG Type II and THG KD*P crystals
- C: SHG Type II and FHG KD*P crystals
- 2: for use with GCR-3 lasers
- 4: for use with GCR-4 lasers

**Output Power Table**

<table>
<thead>
<tr>
<th></th>
<th>GCR-3</th>
<th>GCR-4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>λ (nm)</strong></td>
<td>-10</td>
<td>-30</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>650 mJ</td>
<td>750 mJ</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>7-9 ns</td>
<td>7-9 ns</td>
</tr>
<tr>
<td>Energy Stability</td>
<td>±1%</td>
<td>±1%</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>400 mJ</td>
<td>330 mJ</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>5-7 ns</td>
<td>5-7 ns</td>
</tr>
<tr>
<td>Energy Stability</td>
<td>±1%</td>
<td>±1%</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>200 mJ</td>
<td>160 mJ</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>4-6 ns</td>
<td>4-6 ns</td>
</tr>
<tr>
<td>Energy Stability</td>
<td>±1%</td>
<td>±1%</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>80 mJ</td>
<td>40 mJ</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>4-6 ns</td>
<td>4-6 ns</td>
</tr>
<tr>
<td>Energy Stability</td>
<td>±1%</td>
<td>±1%</td>
</tr>
</tbody>
</table>

**Output Characteristics**

| PRF optimum | 10 | 30 | 10 | 30 |
| PRF range   | 2-20 | 4-40 | 2-20 | 4-40 |
| Spatial Mode | Uniphase | Uniphase | Uniphase | Uniphase |
| Depolarization @ 1064 nm | ≤5% | ≤5% | ≤5% | ≤5% |
| Beam Diameter | 7.0 mm | 7.0 mm | 8.5 mm | 8.5 mm |
| Beam Divergence | ≤0.5 mrad | ≤0.5 mrad | ≤0.5 mrad | ≤0.5 mrad |
| Beam Pointing Stability | ≤0.5 mrad | ≤0.5 mrad | ≤0.5 mrad | ≤0.5 mrad |
| Output Pulse Temp. | ≤500 ps | ≤500 ps | ≤500 ps | ≤500 ps |
| Average Power Stability | 9% | 5% | 9% | 5% |
| Linewidth @ 1064 nm | ≤1.8 cm⁻¹ | ≤1.0 cm⁻¹ | ≤1.8 cm⁻¹ | ≤1.0 cm⁻¹ |
| w/LCE-1 (optional) | ≤0.2 cm⁻¹ | ≤0.2 cm⁻¹ | ≤0.2 cm⁻¹ | ≤0.2 cm⁻¹ |
| w/ELM-2 (optional) | ≤0.02 cm⁻¹ | ≤0.02 cm⁻¹ | ≤0.02 cm⁻¹ | ≤0.02 cm⁻¹ |

1. Specifications subject to change without notice.
2. Unless otherwise noted, specifications are given for standard (nominal 8 usec pulse width) Q-switched operation, and do not include insertion loss of accessories.
3. Output powers of Model 6300 are 20% less than specified above.
4. Shorter pulse modes, included at an extra cost, reduces temporal pulse width by a factor of about three (to 2.5 usec @ 1064 nm) and reduces pulse energy by approximately 10%.
5. Not available on 6300 versions.
6. For >95% of pulses.
7. Line width specifications include phase jitter and are for the Model 6300.

**ICE-1 Intracavity Etalon**

**6300 Injection Seeder**

**DHS-2 Dichroic Harmonic Separator**

**PDL-3 Pulsed Dye Laser**

**DHS-1 Dichroic Harmonic Separator (mounts inside PDL-3)**
Far field (0m from the output coupler) beam pointing stability data taken for 9 consecutive shots from a GCR-4-30 operating at 1064nm.

Beam pointing stability measurement.
YAG - Laser \[\rightarrow 20\text{m} \rightarrow\] Interferometer

Slow shift (relative vertical position) \(\sim 1\text{cm}\)

Small error

Feed back

Slow beam pointing - drift from laser.

\(\phi = \phi_2\)

Horizontal oscillation

\(\phi_1\)

Roll swing

\(\theta_{gi}\)

Mass center?
Laser-Compton Beam Size Monitor

T. Shintake
16 Dec. 1991

Optical Table
In Laser Building
- 2 m

Beam Transfer Tube (vac)
In Aco. Tunnel
- 30 m

Vertical Table
on Final Q-magnet
- 2 m

Focal point

YAG-Laser

Support table
\( \Delta x < \pm 0.5 \text{ mm} \)
\( \Delta x' < \pm 0.5 \text{ mm} \)
\( \Delta x'' < \pm 6 \text{ rad} \)

Expander x 6
\( \Delta x < \pm 0.5 \text{ mm} \)
\( \Delta x' < \pm 6 \text{ rad} \)

Reducer x 1/5
\( \Delta x < \pm 0.5 \text{ mm} \)
\( \Delta x' < \pm 6 \text{ rad} \)

\( \Delta x' < \pm 30 \text{ rad} \)

500 mm

\( \phi 0.2 \text{ mm} \)

\( \phi 7 \text{ mm} \)

\( \phi 7 \text{ mm} \)

\( < 30 \mu \text{rad} \)

\( \text{feedback} \)

\( < 0.1 \mu \text{m} \)

Jitter Tolerances of Laser Beam Transport System

* Notice: Expander and reducer must be stably supported to satisfy \( \Delta x' < \pm 6 \text{ rad} \) (jitter and drift).
Horizontally Injected Error.

Top View

$Q.C - 1$

$\Delta z_i, \theta z_i$

$400 \mu m$

$200 \mu m$rad.

$2000$

$500$

$f = 500$

$< 100 \mu m$

$\beta$-function

$< 100 \mu m.$

Finally, Torque

$\Delta z_i < 0.4 \text{ mm} (40 \mu m)$

$\theta z_i < 0.2 \text{ mrad} (20 \mu $rad$.)$
### Expected Accuracy (at 60 nm)

<table>
<thead>
<tr>
<th>Error Sources</th>
<th>Expected Beam Size Measurement Error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical Error on γ-ray Measurement</strong></td>
<td></td>
</tr>
<tr>
<td>$300 \times 10^3$ γ-ray/pulse</td>
<td>&lt; ±3 %</td>
</tr>
<tr>
<td>$30 \sim 100$ data points</td>
<td></td>
</tr>
<tr>
<td><strong>Electron Beam</strong></td>
<td></td>
</tr>
<tr>
<td>Position Jitter</td>
<td>$σ_j &lt; 20 \text{ nm}$</td>
</tr>
<tr>
<td>Injection angle error</td>
<td>$θ_i &lt; 200 \text{ μrad}$</td>
</tr>
<tr>
<td><strong>Laser Beam</strong></td>
<td></td>
</tr>
<tr>
<td>Finite Spot Size Effect (D 200 μm)</td>
<td>( +14 %)</td>
</tr>
<tr>
<td>Eliminate by correction</td>
<td></td>
</tr>
<tr>
<td>Missalignment</td>
<td>$Δx &lt; 20 \text{ μm}$</td>
</tr>
<tr>
<td></td>
<td>$Δθ &lt; 40 \text{ μrad}$</td>
</tr>
<tr>
<td>Non-uniform beam profile effect</td>
<td></td>
</tr>
<tr>
<td>Interference visibility $&gt; 0.95$</td>
<td>&lt; 13 %</td>
</tr>
<tr>
<td>Coherency</td>
<td>line width $&lt; 0.003 \text{ cm}^{-1}$</td>
</tr>
</tbody>
</table>

**Total Error** = -3 ~ +15 %

for 60 nm beam : Error = -2 ~ 9 nm
**Mode Pattern Measurement**

- **Piezo Mover**
- **Laser**
- **5μm gold wire**
- **Tele Scope**

Mathematical expressions:

\[ E_1 e^{j\phi_1} + E_2 e^{j\phi_2} \]

Interference:

\[ E_1 e^{-j(\phi_1 + \Delta\phi)} + E_2 e^{-j(\phi_2 + \Delta\phi)} \]

Graphical representation:

- Power variation with distance
- Visibility graph at 532nm
Preparations:

Nd:YAG-Laser

ordered → Delivery

Spatial Filter
Laser Beam Position Sensor

Non Focused Laser Beam Test.
Spatial Mode Measurement
Pointing Stability
Power Stability
Jitter, etc.
Wave Front, P

Laser Beam Alignment Tool
Vertical Table
Vacuum Chamber
Mirrors, Lens
Isolators, Shutter
Mounting

Focused Field Measurement

Mode Pattern
Spatial Mode Stability, etc.

Transport to SLAC

Time Schedule (KEK - side)
Laser - System

T. Shinohara
19 Sep. 1991
High-resolution Beam Position Monitor for Linear Collider.

T. Shintake, H. Hayano.
Beam Size and Position Monitors using liquid jets

F.Villa

SLAC
Measuring beam size with liquid jets

Solid wires do not survive beam densities encountered in the final focus spot. Therefore conventional wire scanners cannot provide information about beam size at full beam intensity. So far there are three proposed solutions to the problem:

1) Beam generated plasma (ion time of flight) (Chen, Orsay)
2) Laser standing wave (Shintake, KEK)
3) Liquid wires (jet or microdroplets) (Villa, SLAC)

The basic idea is to intercept the beam with a liquid jet, that automatically replenishes itself after the beam blows up a short section. A liquid jet is unstable (it tends to fragment in small spheres) and the location of the spheres can be accurately measured: the spheres themselves can be used to probe the beam size. The signal(s) from the interaction can be the same as in solid wires.
Intersecting with a liquid jet

A liquid jet formed by a small diameter nozzle can be used just as a wire scanner. The liquid must have the following properties:

1) Liquid around room temperature
2) Low (ultra low) vapor pressure
3) Compatible with material(s) used in the vacuum system.
4) Short radiation length (high Z, dense)

The first liquid that comes to mind is Hg; but it does not have ultra low vapor pressure, is not well tolerated by getter pumps, etc. All Hg's problems could be handled, in various ways. We may return to it at a later stage. (Hg is dense, and high Z)

There are two candidates:

Silicone liquids (diffusion pump oils)

Low temperature eutectic alloys.

If you have other suggestions, please come forward.
Jet formation and properties.

Properties of a liquid: (units are MKSQ)

\[ \rho = \text{density} \]
\[ \eta = \text{viscosity} \]
\[ \sigma = \text{surface tension} \]

Nozzle parameters

\[ r = \text{radius at exit} \]
\[ L = \text{length of the (slowly) converging section} \]
\[ \Delta P = \text{pressure applied to the nozzle} \]

The velocity of a jet leaving a (slowly) convergent nozzle is:

\[ V = \frac{\Delta P r^2}{8L\eta} \]

This is the definition of viscosity.

The flow (volume/unit time) is

\[ Q = \frac{\pi \Delta P r^4}{8L\eta} \]

The minimum velocity necessary to form a jet is

\[ V_{\text{min}} = 2 \left( \frac{\sigma}{\rho r} \right)^{\frac{1}{2}} \]
A liquid jet is unstable because surface tension will force it to collapse in separate spheres. Essentially, any perturbation at the nozzle's exit is quickly amplified. If the perturbation is not "driven", the breakup is not very repeatable. If the perturbation is introduced appropriately, jet breakup occurs with great precision.

The length of the jet, before fragmenting into separate spheres, is given by (approximately)

$$\Lambda_{\text{m}} = k\nu\left(\frac{8r^3\rho}{\sigma}\right)^{\frac{1}{2}}$$

Combining these expressions, under the assumption of constant aspect ratio of the nozzle ($r/L = \text{const}$), we see that, for constant jet length, the pressure must increase as $r^{5/2}$;

$$\Lambda_{\text{m}} = k\Delta P \frac{r}{L} \frac{1}{8\eta} r^{\frac{5}{2}} \left(\frac{8\rho}{\sigma}\right)^{\frac{1}{2}}$$
Experimentally, for the eutectic alloy of Ga/In/Sn, we have a jet length of 7 cm for a pressure of 300 psi, a diameter of the nozzle of 10 microns, and an aspect ratio of 1/15 (sapphire nozzle). This scaling has been roughly confirmed by a 4 micron jet (the smallest so far), where the pressure required was about 3000 psi.

If the diameter is reduced to 1 micron, leaving other parameters unchanged, the pressure required will be 95000 psi. For a 0.1 micron, the pressure goes to 30 million psi, a rather unpractical value. Obviously the nozzle parameters must be changed for small diameter jets.

i) The aspect ratio of a nozzle can be reduced to 1/3. This improves the jet stability, because there is less space to develop turbulence.

ii) The unbroken jet length can be reduced (to 1 mm or less).

iii) By increasing the jet temperature (by about 25 K above room temperature), the viscosity drops by a factor of 3, and the surface tension is reduced by 20%.

The changes in aspect ratio, jet length, viscosity and surface tension make a substantial difference in the pressure required for 1 micron jet (100 psi), and bring the 0.1 micron diameter jet within an accessible pressure range (30000 psi).

A difficult problem: small orifices are easy to plug, i.e. one needs a liquid free of particulate contaminants. The In/Ga/Sn alloy is very dense, and common particles should float in the liquid. Silicone oil is not dense, and may have serious problems, if used with small (a few microns) nozzles. Filters with the necessary finesse are not easy to find (and to use).
The nozzle problem

Some of the components necessary to implement a jet are "available": pumps up to 90000 psi, ancillary plumbing, filters (albeit not as fine as we need), etc. Good quality nozzles are available in the 10 micron diameter (and up) range.

The nozzles we have used so far are very poor, both geometrically (good geometry is necessary for a reliable jet formation), and mechanically (i.e. they fail under pressure).

Recently we have made some promising nozzles, by quasi-melting the tip of a glass capillary, and grinding the end surface to a flat (as per G. L. Switzer, Rev. Sci. Instrum. 62(11), Nov 1991, pag. 2766 and segg.)
Use of spherical droplets

Any jet will break into spheres. If a periodic perturbation is applied to the pressure driving the nozzle (for example, using a piezoelectric pressure modulator), the spheres are accurately spaced and uniform in size. The spheres can be electrically charged; by measuring the charge carried by each sphere, knowing the potential of the (conducting) jet we can measure the sphere diameter.

Given a quasi steady stream of spheres, their relative distance (and perhaps size) can be measured with good (but as yet unknown) precision. If one of the spheres intercepts the beam, its position can be interpolated from the leading and trailing fractions of the stream of spheres. Therefore the position of the interacting sphere can be known accurately.
Other ideas

The formation of an extremely small diameter jet (below 0.1 microns) may not be practical. At the same time, the bremsstrhalung signal becomes small (the radiation length of the Ga/In/Sn alloy is 1.8 cm, so that a 0.1 micron "wire, or an equivalent sphere gives roughly 5000 photons, for a 1 micron wide flat beam). This signal is still appreciable, but in a real case, in presence of background, the usual criteria of a 3 to 1 ratio between wire diameter and measurable beam size may not hold. With these caveats in mind, one can think of two ways to make small spheres in a controlled fashion, without the use of high pressure:

1) A small (less than 0.1 micron) target sphere could be launched to cross the beam by using an microscopic version of an electromagnetic launcher.

2) There are chaotic instabilities in the formation of ion beams from liquid metal ion sources (LMIS). These instabilities manifest themselves in the ejection of matter (very small size spheres, down to 100 Angstroms). A proper attractor can be introduced in the LMIS to stabilize the mechanism. (see V.V. Vladimirov, et al. J. Vac. Sci. Technol., B9, (5), Sept 1991, 2582.)

I have done some calculations on both versions: the conclusions are that "something" will be launched in a controllable fashion, but nothing can replace experimentation.
Conclusions

The smallest jet obtained so far is about 4 micron diameter. With the new glass nozzle technique we should be able to make progress.

A short jet, 0.1 micron diameter, 1 mm length seems possible (on paper).

As soon as a reliable set up is completed, we will proceed to study jet properties, and sphere formation, control and timing.

We are beginning to study other techniques to see if it is possible to reduce the size of the probe below 0.1 micron.
glass tube

-26-92

#3

30X
glass tube with center hole 1000X.

2-26-92
Design of FFTB Optics

2/28/1992
K. Oide (KEK)

- Parameters
- Chromaticity Correction
- Optimization
- Tolerance
- An Extension
K. Brown, R. Helm, J. Irwin, G. Roy
(SLAC)

N. Yamamoto (KEK)


FFTB — a milestone to future linear colliders

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>FFTB</th>
<th>(JLC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy</strong></td>
<td>$E$ 50 GeV</td>
<td>50 GeV</td>
<td>500 GeV</td>
</tr>
<tr>
<td><strong>Emittance</strong></td>
<td>$\xi_x 3\times10^{-5}$ m</td>
<td>$3\times10^{-5}$ m</td>
<td>$5\times10^{-6}$ m</td>
</tr>
<tr>
<td></td>
<td>$\xi_y 3\times10^{-5}$ m</td>
<td>$3\times10^{-6}$~$3\times10^{-7}$ m</td>
<td>$5\times10^{-8}$ m</td>
</tr>
<tr>
<td><strong>Spot Size @IP</strong></td>
<td>$\sigma_x^* 1.2$ $\mu$m</td>
<td>1.0 $\mu$m</td>
<td>0.3 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>$\sigma_y^* 1.2$ $\mu$m</td>
<td>60~20 nm</td>
<td>2.8 nm</td>
</tr>
<tr>
<td><strong>Beta func. @IP</strong></td>
<td>$\beta_x^* 5$ mm</td>
<td>3 mm</td>
<td>24 mm</td>
</tr>
<tr>
<td></td>
<td>$\beta_y^* 5$ mm</td>
<td>0.1 mm</td>
<td>0.12 mm</td>
</tr>
<tr>
<td><strong>Length of free area</strong></td>
<td>$L^* 0.4$ m</td>
<td>1.4~3 m</td>
<td></td>
</tr>
<tr>
<td><strong>Pole-tip field</strong></td>
<td>$B_0 1.4$ T</td>
<td>1.4 T</td>
<td></td>
</tr>
<tr>
<td><strong>Demagnification</strong></td>
<td>$M_g 1/30$</td>
<td>$1/300$</td>
<td>$1/300$</td>
</tr>
<tr>
<td><strong>Particles/Bunch</strong></td>
<td>$N 3\cdot10^{10}$</td>
<td>$1.1\cdot10^{10}$</td>
<td>$2\cdot10^{10}$</td>
</tr>
<tr>
<td><strong>Length/Beam</strong></td>
<td>$L 140$ m</td>
<td>180 m</td>
<td>240~500 m</td>
</tr>
<tr>
<td><strong>Bunch Length</strong></td>
<td>$\sigma_z 0.5$ mm</td>
<td>0.5 mm</td>
<td>0.1 mm</td>
</tr>
<tr>
<td><strong>Chromaticity</strong></td>
<td>$\xi_z 8600$</td>
<td>2000~4000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\xi_y 9000$</td>
<td>16000~3600</td>
<td></td>
</tr>
<tr>
<td><strong>Momentum bandwidth</strong></td>
<td>$\Delta p/p \leq 0.3%$</td>
<td>$\pm 0.3%$</td>
<td>$\pm 0.3%$~$1.5%$</td>
</tr>
</tbody>
</table>
• Chromaticity correction

• Spot size at the focal point blows up due to the chromaticity of final lenses.

\[ \sigma^2 = \sigma_0^2 \left(1 + \xi^2 \left(4 P/p^2 \right) \right) \]

\[ \xi_{x,y} = \int_{0}^{s} K \beta x_{y} ds \approx \frac{f_{x,y}}{\beta_{x,y}} \]

In the case of FFTB, \( \xi_{x,y} \approx 9000, |P/P| < 0.3\% \) gives \( \sigma = 16 \sigma_0 \) in both direction.

• The classical method of chromaticity correction is to put sextupoles at dispersion.

• Geometric aberrations of sextupoles are cancelled by \(-I\) transformer between two identical sextupoles up to 2nd order. (K. Brown)

• Non-interlaced 2 family sextupoles is the best way to realize the K. Brown's idea.

• Further improvement is possible by wideband additional sextupoles (R. Brinkmann) more optimized \(-I\) trans. (J. Irwin) tolerance
$\sigma_x^*(\mu \text{m})$

$I\Delta p/\rho (\%)$, uniform distribution

$\sigma_y^*(\text{nm})$

$I\Delta p/\rho (\%)$, uniform distribution
Aberrations

(a) Finite thickness of sextupoles.
\[
\frac{\Delta \sigma_{y}^{*2}}{\sigma_{y}^{*2}} = \frac{5}{12} \frac{K^4 \beta_y^* \epsilon_y^* l_s^2}{\gamma^2}.
\]

\( \beta_y^* \): \( \beta_y \) @ sext.

\( l_s \): thickness

(b) Chromo-geometric aberration — breakdown of -I trans.
\[
\frac{\Delta \sigma_{y}^{*2}}{\sigma_{y}^{*2}} \propto \frac{x_y y_x^2 \epsilon_x (4p)^3}{r \theta^3 l_b}
\]

\( \theta \): bend angle

\( l_b \): length of bend

(c) Synchrotron radiation — energy mismatch between CCS and final \( \theta \).
\[
\frac{\Delta \sigma_{y}^{*2}}{\sigma_{y}^{*2}} = \frac{55}{1213} \frac{R e^* e y^5 \Theta^3}{l_b^2} \frac{\xi_y^2}{\xi_x^2}
\]

energy spread by bends between YCCS and final guads.

Total aberration is minimized by choosing bend angle \( \theta \). The length of bend is limited by the allowable magnitude of the aberration.
Tolerances

- Typical tolerance for $\Delta \sigma / \sigma = 10\%$

- r.m.s. vertical displacement of Bend, Quad, Sext.
  $\Delta y_{rms} \leq 4 \mu m$

- r.m.s. horizontal displacement of Bend, Quad, Sext.
  $\Delta x_{rms} \leq 1 \mu m$

- r.m.s. strength error of Quad & Sext.
  $(\Delta k/k)_{rms} \leq 2 \times 10^{-5}$

- r.m.s. skew rotation error of Quad & Sext.
  $\Delta \theta_{rms} \leq 25 \mu rad$

- Diffusion rate of the ground.
  $<(\Delta x^2) > \sim <(\Delta y^2) > \sim A \cdot T \cdot L$

  $A \cdot T \leq 10^{-11} m$
- An extension – 2 or 3 spot size monitors in the same time??

- If $L^*$ is increased from 0.4m to 0.8m by changing QC guads, QX1, and sextupoles, then:
  
  \[
  \begin{align*}
  \Delta L^* & \quad \text{becomes} \quad 4\% \text{ bigger}, \\
  \Delta \sigma^* & \quad \text{"} \quad 4\% \text{ bigger}, \\
  \text{Quadrupoles becomes weaker,} \\
  \text{SD1 sextupole 20\% stronger,} \\
  \end{align*}
  \]

  still looks all right.

Having 2~3 monitors at the same time increases the total reliability of FF18 much.

一石二鳥  ↔  追二獲無
Tolerances and Correction Techniques

Ghislain Roy
and FFTB Optics group

February 28, 1992
Outline

Tolerances

Derivation
Stability Tolerances
Capture Tolerances
Acceptability Window

Correction Techniques

( Beam Based Alignment )
Quadrupole Tuning using Orbit Bumps
Global Correction
Feedbacks
Study of aberrations and tolerances using Hamiltonians

Hamiltonian-Potential \( = H(x,y) \)

Kick \( \Delta x' = - \frac{\partial H}{\partial x} \) \( \Delta y' = - \frac{\partial H}{\partial y} \)

Need a criterion for Tolerances

Ability to detect a 10% spot size increase (demonstrated at the SLC)
Translates into ability to cancel an aberration to the 2% spot size increase level.

Canonical value: 2% change in the beam size at the IP

The condition is now

\[ \Delta \sigma_\gamma \leq \frac{1}{5} \sigma_\gamma \]

\( (\Delta x')_{\text{rms}} \leq \frac{1}{5} \sigma_x \)

Get the RMS tolerance on all magnets

\[ \frac{1}{\epsilon_q} = \sum_{\epsilon_q} \frac{1}{\epsilon_i} \]

All magnets are not of equal importance; assign different fraction of the tolerance budget to different groups:
Y = A * (X - B)^2 + C

A = 16.35  STD DEV = 1.542
B = -0.5475  STD DEV = 6.6630E-02
C = 17.14  STD DEV = 3.400

RMS FIT ERROR = 11.44
Chi-square = 0.9887

KNOB (SX_WAIST)

KNOB (SX_WAIST) STRT=-3.000 STEPS= 5 SIZE= 1.500

31-JAN-92 00:20:0

Y = A * (X - B)^2 + C

A = 13.71  STD DEV = 1.470
B = 0.6275  STD DEV = 5.5274E-02
C = 5.783  STD DEV = 1.410

RMS FIT ERROR = 4.610
Chi-square = 1.253

KNOB (SX_WAIST)

KNOB (SX_WAIST) STRT=-3.000 STEPS= 5 SIZE= 1.500

31-JAN-92 00:29:1
\[ H = \frac{h_s}{2} (x^2 - y^2) \]

\[ \Delta y \leq \frac{1}{E_y} \sqrt{\frac{\varepsilon_y}{\beta_y}} \quad \text{for tolerance} \]

**Vertical Steering Tolerances**

- **Fq**: 60 nm
- **worst quad**: 0.46 μ
- **EHS**: 0.18 μ
\[ H = k_q \sin(2\theta) \times y \]

\[ \theta \leq \frac{1}{10 k_q \sqrt{p \cdot q}} \sqrt{\frac{\epsilon_\theta}{\epsilon_x}} \]  

(V only)

Rotation Tolerances (roll)

[Bar chart showing rotation tolerances in radians]

FG

33 μrad

[Property of doubles: both elements have the same rotation tolerances; here = 60 μrad]

RHS

40 μrad

485
\[ H = \frac{\Delta \frac{q}{2}}{z} (x^2 - y^2) \]

\[ \Delta \frac{q}{2} \leq \frac{1}{z L \beta_{ox} (\beta_2, \beta_2)} \]

Relative Strength Tolerances

\[ \Delta k/k \]

\[ FQ : \quad 2 \times 10^{-5} \quad (9 \times 10^{-5} \text{ for QX1}) \]

\[ RHS : \quad 7.3 \times 10^{-5} \]

Note: ORsay BSM with a slit of hoop will not be very sensitive to this effect.

One can move the waist around with no damage on spot size measurement laser or wire at IP so these values OK.
\[ H_{ns} = \frac{\hbar s}{3!} \left( x^3 - 3xy^2 \right) \quad H_{ss} = \frac{\hbar s^2}{3!} \left( 3x^2y - y^3 \right) \]

\[ P_{ns} \leq \text{Min} \left[ \frac{\sqrt{2}}{50\pi \beta x \sqrt{1 + \frac{\beta y}{\beta x}^4}}, \frac{1}{50\pi \beta y} \right] \]

\[ b_{s,ss} \leq \text{(idem but exchange x and y)} \]

Sextupole Content Tolerances

\[ F_P : \quad b_{ns} \leq 5 \times 10^{-3} \text{ m}^{-2} ; \quad b_{ss} \leq 4 \times 10^{-2} \text{ m}^{-2} \]

(sekt. corr.)

Worst: \((\Phi C3)\) \( b_{ns} \leq 12 \times 10^{-3} \text{ m}^{-2} ; \quad b_{ss} \leq 6 \times 10^{-3} \text{ m}^{-2} \)

RMS: \( P_{ns} \leq 9 \times 10^{-3} \text{ m}^{-2} \), \( b_{ss} \leq 6 \times 10^{-3} \text{ m}^{-2} \)

\[ \text{Magnets received from INFN meet and exceed these tolerances.} \]
A MATTER OF MULTIPLIERS

beam offset $\theta_2 = \text{displacement of } 1 \times \text{Multiplier}$

Horizontal Alignment Tolerances

(dispersion, normal and skew quad.)
Vertical Alignment Tolerances

dispersion, normal, and skew quad. effects

Y-axis: $10^{-7}$ to $10^{-3}$

Bar chart showing vertical alignment tolerances for different labels (e.g., Q5, QA1, QA2, etc.).
### TABLE 2: IMPORTANT FFTB STABILITY TOLERANCE

<table>
<thead>
<tr>
<th>Section</th>
<th>Element</th>
<th>Tolerance</th>
<th>Attribute</th>
<th>Aberration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD</td>
<td>Quads</td>
<td>0.2µ</td>
<td>Δx</td>
<td>Steering</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12nm</td>
<td>Δy</td>
<td>Steering</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50µ</td>
<td>Δx</td>
<td>Dispersion</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.7µ</td>
<td>Δy</td>
<td>Dispersion</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16µrad</td>
<td>Tilt</td>
<td>Skew Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.10⁻⁵</td>
<td>Δk_q/k_Q</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.10⁻⁴</td>
<td>Bs/Bq at .7a</td>
<td>N or Sk Sext</td>
<td></td>
</tr>
<tr>
<td>FT</td>
<td>Mid Quad</td>
<td>1.5µ</td>
<td>Δx</td>
<td>Dispersion</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2µ</td>
<td>Δy</td>
<td>Dispersion</td>
<td>71</td>
</tr>
<tr>
<td>CCY</td>
<td>Sextupoles</td>
<td>0.9µ</td>
<td>Δx</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4µ</td>
<td>Δy</td>
<td>Skew Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.10⁻³</td>
<td>Δk_s/k_s</td>
<td>Sextupole</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2mrad</td>
<td>Tilt</td>
<td>Skew Sext.</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>End Quad</td>
<td>2.10⁻⁴</td>
<td>Δk_q/k_Q</td>
<td>Normal Quad</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.1mrad</td>
<td>Tilt</td>
<td>Skew Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Center Quad</td>
<td>1.0µ</td>
<td>Δx</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3µ</td>
<td>Δy</td>
<td>Skew Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Dipole Bend</td>
<td>1.10⁻⁵</td>
<td>Δk_B/k_B</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
<tr>
<td>BX</td>
<td>Mid Quad</td>
<td>4µ</td>
<td>Δy</td>
<td>Dispersion</td>
<td>71</td>
</tr>
<tr>
<td>CCX</td>
<td>Sextupoles</td>
<td>3.5µ</td>
<td>Δx</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5µ</td>
<td>Δy</td>
<td>Skew Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>End Quad</td>
<td>6.10⁻³</td>
<td>Δk_q/k_Q</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.3mrad</td>
<td>Tilt</td>
<td>Skew Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Center Quad</td>
<td>.7µ</td>
<td>Δx</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.0µ</td>
<td>Δy</td>
<td>Skew Quad</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Dipole Bend</td>
<td>2.10⁻⁵</td>
<td>Δk_B/k_B</td>
<td>Normal Quad</td>
<td>72</td>
</tr>
</tbody>
</table>

† This steering tolerance, corresponding to an FP jitter of .2σ, need not be achieved for spot size measurement techniques insensitive to spot jitter.
Capture Tolerances

The set of tolerances such that optical, beam based tuning can be carried out successfully and the correction does converge.

Specifications for vertical alignment is 30 microns.

Capture is achieved for up to 50 microns. A value of 100 microns is possible if we provide a correction for a chromatic skew quadrupole term (x y f).

More simulations needed here!

Acceptability Window

Bandwidth 0.4%  
Energy jitter 0.1% is acceptable for a typical 0.2% energy spread

Very large range for beta functions matching allows for total reversal of the line.

Horizontal spot size linear with the emittance to keep 10 sigmas clearance. Idem for the vertical plane after a 2 x increase.

Incoming dispersion estimated at .3 to .5 sigma level but we can correct up to 7 sigmas of dispersion at the IP.

Two coupling terms affect the vertical spot size. One only created inside FFTB. Ability to correct 20% amplitude coupling.

Jitter < 0.2 sigma needed for the wire scanners. Tolerance on spot size is 0.3 sigma.
"LARGE [10^4] BETA FUNCTION ADJUSTABILITY"

(for annular resonances)
**BEAM-BASED SEGMENT (QUAD)**

**ALIGNMENT**

Hinge Point

\[ k \pm \Delta k \]

Base Quad

\[ x(k+\Delta k) \]

\[ x(k) \]

**MODULATE** Strength of each Quad and Move to Make Orbit Stationary

Hinge Point

Base Quad

Hinge Angle

Hinge to put Beam through Base Quad

**TOOLS**

1) BPMs 3-4\mu s.s. Precision - 1\mu m MS Precision

2) Magnet Moves 2\mu m Every Quad
TABLE 3: ACCURACY OF BEAM-BASED QUADRUPOLE ALIGNMENT PROCEDURE

<table>
<thead>
<tr>
<th>Segment</th>
<th>Section</th>
<th>Element</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BM</td>
<td>Q5</td>
<td>110</td>
<td>.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QA1</td>
<td>60</td>
<td>.42</td>
</tr>
<tr>
<td>2</td>
<td>CCX</td>
<td>QN2</td>
<td>2.9</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QN1</td>
<td>.71</td>
<td>.57</td>
</tr>
<tr>
<td>3</td>
<td>BX</td>
<td>QT2</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QT3</td>
<td>1.3</td>
<td>.55</td>
</tr>
<tr>
<td></td>
<td>CCY</td>
<td>QM1</td>
<td>.65</td>
<td>.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QM2</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>FT</td>
<td>QM1</td>
<td>1.3</td>
<td>.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QC5</td>
<td>4.4</td>
<td>.9</td>
</tr>
<tr>
<td>5</td>
<td>PD</td>
<td>QC2</td>
<td>15</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QC1</td>
<td>44</td>
<td>3.6</td>
</tr>
</tbody>
</table>

* Tolerances and sensitivities are given in microns.

- Within factor of 2 -
Can tune globally later!

"Skew Quad or Dispersion Aberration"
(a) SQUARING THE \eta \text{ function}

FFT890F with "Squared" \eta\ s and phases 1991/02/10

\[
\begin{align*}
\sqrt{\beta_x} \text{ and } \sqrt{\beta_y} \\
\eta_x \text{ and } \eta_y (m)
\end{align*}
\]
QUADRUPOL - TUNING n. ORBIT BUMPS

1) 1m MS BPMs
2) 6H & 6V STEER. Dipoles TO LAUNCH & TERMINATE BUMPS
3) FAST IP - M FIELD
Quadrupole Tuning

Prerequisites:

- "Square lattice": modify the lattice to have perfect -I for the CCS and -M magnifiers. Dispersion function is now aligned on the horizontal beta function.

- Correctors (6H and 6V) used for tuning only, NOT STEERING

- BPMs with 1 micron precision

- Trims on quadrupoles

Method

Launch one of sixteen different bumps across the precise -I and -M sections and look at signals on BPMs or Wire Scanners.

Bumps are limited by a required clearance of at least 8 sigmas.

The accuracy of the method allows us to tune the quadrupoles to better than the required tolerances.

Sextupole offsets are also determined to better than tolerances.
**TABLE 4: ACCURACY OF BEAM-BASED QUADRUPOLE TUNING PROCEDURE**

<table>
<thead>
<tr>
<th>Section</th>
<th>Element</th>
<th>Tolerance $\delta k/k \times 10^{-4}$</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCX</td>
<td>End Quads</td>
<td>3.3</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Mid Quads</td>
<td>12</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Central Quad</td>
<td>210</td>
<td>.6</td>
</tr>
<tr>
<td>BX</td>
<td>End Quads</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>QT2</td>
<td>15</td>
<td>.6</td>
</tr>
<tr>
<td></td>
<td>QT3</td>
<td>5.1</td>
<td>1.5</td>
</tr>
<tr>
<td>CCY</td>
<td>End Quads</td>
<td>0.9</td>
<td>.6</td>
</tr>
<tr>
<td></td>
<td>Mid Quads</td>
<td>6.7</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Central Quad</td>
<td>270</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Exceeds Tolerances!

**TABLE 5: ACCURACY OF SEXTUPOLE ALIGNMENT PROCEDURE**

<table>
<thead>
<tr>
<th>Section</th>
<th>H or V</th>
<th>Tolerance $\mu$</th>
<th>Sensitivity $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCX</td>
<td>H</td>
<td>3.5</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>3.5</td>
<td>2.9</td>
</tr>
<tr>
<td>CCY</td>
<td>H</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>1.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Global Correctors

A global corrector is a knob used to cancel one aberration at the IP. Global correctors are orthogonal and use the spot size or position at the IP for tuning.

Global correctors provide the final touch to the tuning of the optics. They are needed if some tolerances cannot be achieved or if they cannot be held for a long enough time.

There are 13 global correctors associated with three time scales.
### Table 1: Low Order Aberrations and Global Correctors

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Generator</th>
<th>Cause of loss of luminosity</th>
<th># of knobs</th>
<th>Knob Name (Corrector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_0$</td>
<td>$x', y'$</td>
<td>horiz. and vert. steering</td>
<td>2</td>
<td>dipoles at FQ</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>$x'\delta, y'\delta$</td>
<td>dispersion</td>
<td>2</td>
<td>dipoles in FT</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>$x'^2, y'^2$</td>
<td>waist motion</td>
<td>2</td>
<td>trims on final doublet</td>
</tr>
<tr>
<td></td>
<td>$x'y'$</td>
<td>coupling</td>
<td>1</td>
<td>skew quad. in FT</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>$x'^2\delta, y'^2\delta$</td>
<td>chromaticity</td>
<td>2</td>
<td>main sextupoles</td>
</tr>
<tr>
<td></td>
<td>$x'^3, x'y'^2$</td>
<td>sextupole</td>
<td>2</td>
<td>sextupoles in FT</td>
</tr>
<tr>
<td></td>
<td>$y'^3, x'^2y'$</td>
<td>skew sext.</td>
<td>2</td>
<td>skew sext. in FT</td>
</tr>
</tbody>
</table>

| Variable (linac) | $xx', x'^2, yy', y'^2$ | $\beta$ and $\alpha$ mismatch incoming dispersion | 6 | quads in BM |
|                  | $x'\delta, y'\delta$ | incoming dispersion             |   |             |
|                  | $xy', x'y'$          | incoming coupling              | 2 | skew quads in BM |
Feedback

Launch and Energy Feedback  (see Fatin)

Five remarkable points at the FFTB:
- 4 sextupoles and 1 final doublet

Important: maintain the relative positions between all these points.

The CCS are -I transforms and one should always have

\[ \text{BPM}_1 + \text{BPM}_2 = \text{CL} \]

with the control provided by the motion of the electrical center of the central quadrupole (do not use movers)

Prevents normal and skew quad effects from beam offset in sextupoles

The BX and FT are -M magnifiers and one should hold

\[ \text{BPM}_1 + \frac{1}{m} \text{BPM}_2 = \text{CL} \]

Control is provided by dipole correctors (dither coils).

Prevents dispersion effect from beam offsets in high chromaticity regions.

Feedback can hold the beam steady as long as the BPM readings are not drifting; of the order of an hour, after which one should go back to some tuning of the lattice.
Conclusion

No show-stopper in tolerances. Early results from magnet tests and reports at this meeting are very good.

The introduction of global correctors lets us attain looser capture tolerances.

Beam based alignment brings the elements to a factor of 10 better than capture tolerances.

Bump based quadrupole tuning sets the quadrupoles within tolerances. Bumps are possible because the lattice was squared.

Need more studies on capture tolerances and simulation of the tuning process in general.

Schedule

We are slightly ahead since we have already a beam to present...
3D Beam Envelope using Mathematica
Nick Walker
$\beta_x^* = 0.1 \text{ mm}$

$\beta_y^* = 3.0 \text{ mm}$

FFT92

$\eta_x (\text{m})$
FLAT BEAM OPERATION
OF THE SLC

GENERATION IN THE DAMPING RING
T. Raubenheimer

TRANSPORT IN THE RING-TO-LINAC LINE
P. Emma and B. Spence

TRANSPORT IN THE LINAC
C. Adolphsen
SLAC Linear Collider

Overall SLC Layout
RF NORTH DAMPING RING

\[ \alpha_s \approx 1\% \]
\[ \gamma_c = 1.7 \times 10^{-5} \text{ m} \]
\[ \eta_c = 1.5 \text{ m} \]

- SF SEXTUPOLE
- SD SEXTUPOLE

NORTH EXTRACTION KICKER

REFERENCE DRAWINGS # 237-100-04 TO # 237-100-12

RECONCILED WITH DATA BASE OF 31-DEC-88 PFA
RTL (RING TO LINAC) SHOULD PRESERVE
THE SMALL DAMPING RING EMITTANCE (1.6 x 10^-5 m·r)

[Diagram showing particle accelerator stages and cell configurations]

Matching &
Acceleration

Two-Stage Acceleration

\[ \eta_x (NRRL) \approx 0 \]
RING-TO-LINAC TRANSPORT

Bunch Compression:

Factor of 6 reduction: \( R_{56} \approx 0.6 \, \text{m}, \, \sigma_E/E \approx 1\% \).
\( \eta \sigma_E/\sqrt{\beta \epsilon} = 30 \) so dispersion control important.

Emittance Growth:

Growth due to RTL,
- non-zero net dispersion
- betatron chromaticity
- beta mismatch to linac lattice
- x-y coupling,
plus filamentation in the linac.

Diagnostics:

Measure beam phase space with wire scanners at
the end of the RTL at the nominal \( E \) and \( \sigma_E \), or
versus \( E \) for small \( \sigma_E \).
Measure beam position at beginning of the linac as
a function of \( E \) and/or trajectory in the RTL.
PHASE SPACE DILUTION MECHANISMS IN THE SLC BUNCH COMPRESSOR (W. Spence)

**Beta Mismatch (multiplicative):**

\[
\frac{\varepsilon}{\varepsilon_0} = \frac{1}{2} \left[ \frac{\beta}{\beta} + \frac{\widehat{\beta}}{\beta} + \beta \left( \frac{\alpha - \alpha^0}{\beta} \right)^2 \right] = B_0
\]

\[0.64 < \frac{\beta}{\beta} < 1.56, \quad (\alpha^0 = 0)\]

**1st Order Dispersion (additive):**

\[
\frac{\varepsilon}{\varepsilon_0} = 1 + \left( \frac{\eta^2 + \left( \eta \beta + \eta \alpha \right)^2}{2\beta \varepsilon_0} \right)^2 \left( \delta^2 - \langle \delta^2 \rangle \right)
\]

\[\sqrt{\eta^2 + \left( \eta \beta + \eta \alpha \right)^2} < 7 \text{ mm SLC} \quad \sqrt{\eta^2 + \left( \eta \beta + \eta \alpha \right)^2} < 3 \text{ mm FFTB}\]

**2nd Order Dispersion (additive):**

\[
\frac{\varepsilon}{\varepsilon_0} = 1 + \left( \frac{\eta_2^2 + \left( \eta_2 \beta + \eta_2 \alpha \right)^2}{2\beta \varepsilon_0} \right)^2 \left( \delta^2 - \langle \delta^2 \rangle \right)
\]

\[\sqrt{\eta_2^2 + \left( \eta_2 \beta + \eta_2 \alpha \right)^2} < 0.5 \text{ m SLC} \quad \sqrt{\eta_2^2 + \left( \eta_2 \beta + \eta_2 \alpha \right)^2} < 0.2 \text{ m FFTB}\]

**3rd Order Dispersion (additive):**

\[
\frac{\varepsilon}{\varepsilon_0} = 1 + \left( \frac{\eta_3^2 + \left( \eta_3 \beta + \eta_3 \alpha \right)^2}{2\beta \varepsilon_0} \right)^2 \left( \delta^2 - \langle \delta^2 \rangle \right)
\]

\[\sqrt{\eta_3^2 + \left( \eta_3 \beta + \eta_3 \alpha \right)^2} < \sim 20 \text{ m SLC} \quad \sqrt{\eta_3^2 + \left( \eta_3 \beta + \eta_3 \alpha \right)^2} < \sim 9 \text{ m FFTB}\]

**Betatron Chromaticity (multiplicative):**

\[
\frac{\varepsilon_0}{\varepsilon_0} = 1 + \frac{1}{2} \left[ \left( \hat{T}_{116} - \hat{T}_{226} \right)^2 + \left( \hat{T}_{126} - \hat{T}_{216} \right)^2 \right] \delta^2
\]

\[\left( \hat{T}_{116} - \hat{T}_{226} \right)^2 + \left( \hat{T}_{126} - \hat{T}_{216} \right)^2 < 1250\]

**X-Y Coupling:**

\[
\frac{\varepsilon_y}{\varepsilon_{y^0}} = \sqrt{|A|^2 + |B|^2 + |A|^2 \gamma \lambda}; \quad r = \frac{\varepsilon_{y^0}}{\varepsilon_{y^0}}
\]

\[\lambda \equiv \text{tr} \left( A^{-1} B \right) \frac{\sigma_y^0}{\varepsilon_{y^0}} \left( A^{-1} B \right)^T \frac{\sigma_y^0}{\varepsilon_{y^0}}^{-1} \geq 0\]

\[\lambda < 0.2, \quad (|B| = 0) \quad \lambda < 0.02 \quad \text{FFTB}\]
FIRST INDICATION OF 2ND ORDER DISPERSION IN SRTL

\[ \chi = \chi_0 + \eta^2 \left( \frac{\Delta E}{E_0} \right)^2 \]
SRTE Compressor Energy Scan

\[ \Delta Y_{BPM} = R_{nn} (\frac{\Delta \delta}{\delta})^2 + R_{nk} (\frac{\Delta \xi}{\xi})^2 + R_{nnn} (\frac{\Delta \xi}{\xi})^3 \]

\[ \chi = \chi_0 + \eta_1 \delta + \eta_2 \delta^2 + \eta_3 \delta^3 \]

[Graph showing a curve with data points and linear regression lines]

\[ \alpha \approx 1\% \]
EVIDENCE OF 3RD ORDER DISPERSION

\[ x_{119} \text{ vs } \Delta E / E \]

\[ b_0 = -1.15 \times 10^{-2}, \quad b_1 = 29.7, \quad b_2 = -6.1, \quad b_3 = -151 \times 10^{-3} \]

chieq/N=54.361  \quad \Delta E / E  \quad RMS=2.555 \times 10^{-2} \text{ mm}

2. Octupole magnets will be installed in the e-(north) RTL to correct this 3rd order dispersion on February 4, 1992.
TUNING RESIDUAL 2ND ORDER DISPERSION IN THE LINAC

\[
\begin{align*}
T_{166}(0) &= 0.35 \pm 0.15 \text{ m} \\
T_{266}(0) &= -1.41 \pm 0.06 \text{ rad} \\
\|\eta_s\| &= 4.33 \text{ m} \\
\frac{E}{E_0} &= 10.1
\end{align*}
\]

BEFORE TUNING

\[
\begin{align*}
T_{166}(0) &= 0.09 \pm 0.07 \text{ m} \\
T_{266}(0) &= 0.16 \pm 0.03 \text{ rad} \\
\|\eta_s\| &= 0.52 \text{ m} \\
\frac{E}{E_0} &= 1.13
\end{align*}
\]

AFTER TUNING

LONGITUDINAL BPM POSITION [meters]
Segment of the LINAC
Errors:

Quadrupole Misalignments 100 μm rms
BPM Misalignments 100 μm rms
DLWG Misalignments 300 μm rms

Emittance Growth:

Caused by wakefields and dispersion generated by misalignments + steering.
Add correlated energy spread $\sigma_E$ (BNS Damping):
Decreeses wakefield growth
Increases dispersive growth
At $I = 1 \cdot 10^{10}$, the two mechanisms roughly balance.
Run with minimum $\sigma_E$ so lower growth at low $I$.

Simulation:

Study emittance growth by simulating beam transport in a randomly misaligned linac using the above errors. Compute beam matrix ($M$) at the end of the linac for case of zero initial emittance ($\varepsilon_0$). Then,

$$\frac{\varepsilon^2}{\varepsilon_0^2} = 1 + \frac{\text{Tr}(M)}{\varepsilon_0} + \frac{\text{Det}(M)}{\varepsilon_0^2}$$

For this case, $\text{Tr}(M) \gg \sqrt{\text{Det}(M)}$, so ignore last term.
Energy Spread vs position in the LINAC

Without BNS phases

With BNS phases
Emittance Growth in the Linac
\[ \varepsilon/\varepsilon_0 \sim (1 + \varepsilon \tau(M)/\varepsilon_0)^{1/2} \]

\[ \langle \varepsilon \tau(M) \rangle = 6.3 \times 10^{-6} \text{ m-\text{mrad}} \]

\[ I = 1 \times 10^{10} \]

\[ \langle \varepsilon \tau(M) \rangle = 1.9 \times 10^{-6} \text{ m-\text{mrad}} \]

\[ I = 0.5 \times 10^{10} \]

\[ \langle \varepsilon \tau(M) \rangle = 0.9 \times 10^{-6} \text{ m-\text{mrad}} \]
With orbit bumps

\[ \langle \delta \Phi (M) \rangle = 1.6 \times 10^{-6} \text{ m-mk} \]

\[ \Gamma = 1 \times 10^{10} \]
SUMMARY

Generation in NDR:

Should not be a problem at the \( \gamma \varepsilon_y = 3 \cdot 10^{-6} \) level. Need dedicated experiment to verify this.

Transport in the NRTL:

Will need some tuning - diagnostics will improve as part of the SLC effort to increase luminosity and to measure x-y coupling introduced by the linac spin rotator.

Transport in the Linac:

Hard to predict growth because of uncertainty in the errors and the stochastic nature of process. At \( I = 0.5 \cdot 10^{10} \), probably do not need orbit bumps - at higher currents, they should work well.

Best to Date:

With the SDR uncoupled (unintentionally), achieved \( \gamma \varepsilon_y = 1.0 \cdot 10^{-5} \) at \( I = 2.0 \cdot 10^{10} \) for positrons at the end of the linac.
FAST FEEDBACK

I. OVERVIEW: WHY DO WE NEED FEEDBACKS?

II. FFT8 TOLERANCES AT ITS INPUT

- JITTER
- DISPERSION
- POSITION
- ANGLE

III. ENERGY FEEDBACK

IV. POSITION & ANGLE FEEDBACK

---

NOTES:

a) TOLERANCES AND DISCUSSION OF EMITTANCE, $\beta$ ETC. AS WELL AS THIS TALK CAN BE FOUND IN THE "FFT8 OPTICS HANDBOOK".

b) HERE, ONLY SIMPLIFIED FEEDBACK SCHEMES. DETAILS ARE GIVEN IN "UCDHEP MEHR". FOREST ROUSE, MAY 26 1991.

c) MORE ACCELERATOR TUNING TECHNIQUES CAN BE FOUND IN THE FOLLOWING NOTICES:

1. J. SEEHAN, ELC COLLIDER NOTE CN-376, APRIL 23/1990

2. C.E. ADOLPHSEN et al., SLAC-PUB-4720, SEP./1988 AND SLAC-PUB-4902, MARCH/92


4. J. SEEHAN, SLAC-PUB-4752, JAN/89
ENERGY FEED BACK

Fig. 1 is a schematic of the dump line. BPMs 1-4 will be used in the feedback.

For illustration, I will use BPMs 1, 3, 4. For this and other reasons (the contemplated change in bend angle, $x \leq 1.5$), the errors derived here should be considered as an upper limit.

The beam incident on BPM1 has three unknowns: position, angle, and energy. A matrix $M$ (3x3) relates these to the readings of the three BPMs (1, 3, 4):

\[
\begin{pmatrix}
\Delta y_1 \\
\Delta y_3 \\
\Delta y_4
\end{pmatrix} =
M
\begin{pmatrix}
\Delta Y_0 \\
\Delta Y_1 \\
\Delta E
\end{pmatrix}
\]

Inverting the matrix, $\Delta Y_0, \Delta Y_1, \Delta E$ can be obtained from the changes $\Delta y_1, \Delta y_3, \Delta y_4$. Hence, $\Delta E$ is measured and the energy can be corrected back to its nominal value.

E-Feedback does not measure absolute energy, only deviations from some nominal tune energy are measured.

Errors

We aim to measure $\Delta E \sim 0.05\%$ of $E_0$ (50 GeV), i.e., $\Delta E \sim 25$ MeV. The error depends on the BPMs accuracy. Let us take $\sigma_{BPM} = \pm 10\mu$. 

530
\[
\begin{pmatrix}
\pm \sigma_Y \\
\pm \sigma_Y' \\
\pm \sigma_\Delta E
\end{pmatrix} = 
\begin{pmatrix}
1.0 & 0 & 0 \\
-0.1209 & 0.1344 & -0.0135 \\
0.011 & -0.0153 & 0.0043
\end{pmatrix}
\begin{pmatrix}
\pm 10 \mu \\
\pm 10 \mu \\
\pm 10 \mu
\end{pmatrix}
\]

\[
\pm \sigma(\Delta E) = 
\begin{pmatrix}
0.011 & -0.0153 & 0.0043
\end{pmatrix}
\begin{pmatrix}
\pm 10 \mu
\end{pmatrix}
\]

We add the three terms in quadrature to obtain \( \sigma(\Delta E) = \pm 0.02\% \).
DISPERSION, JITTER & POSITION ANGLE FBK

WE NEED THE TOLERANCES OF FFBK TO THESE PARAMETERS AND THE EXPECTATIONS FROM THE ACCELERATOR.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>FFBK TOLERANCE</th>
<th>ACCEL EXPECTATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_y$</td>
<td>± 2.5 mm</td>
<td>≈ ±2 cm(END) + &amp; MISMATCH</td>
</tr>
<tr>
<td>$\eta_y'$</td>
<td>± 0.025 m$^2$</td>
<td>± 0.02 m$^2$(END) + &quot; + &amp;</td>
</tr>
<tr>
<td>JITTER</td>
<td>20% of $\sigma$</td>
<td>≤ 20% of $\sigma$ AT ANY LOCATION</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>± 5$\mu$</td>
<td>≥ ± 30$\mu$.</td>
</tr>
<tr>
<td>$\gamma'$</td>
<td>± 0.04$\mu$</td>
<td>&lt; 1$\mu$.</td>
</tr>
</tbody>
</table>

- DISPERSION:

The quad mismatch (50 line after linac end) is rendered negligible by correcting the quad kicks with available correctors, close to the quads. We have shown that 300$\mu$ mismatch in each quad, when corrected, leads to ≈ 1 mm. $\eta$ and negligible $\eta'$.

The residual dispersion from the linac was not measured but estimated. However, the FFBK has a dispersion suppressor capable of correcting > 2 cm.

- JITTER:

Please note that feedback cannot correct random jitter (shot to shot jitter), although it can be measured (estimated). Tolerance of the FFBK to jitter above was obtained by modeling...


**Position and Angle Feedback**

Fig. 2 shows a schematic of the beam line from the end of the linac to the entrance of the FEBB. The mirror components used in the feedback are marked with red. Briefly, two good BPMs and two pairs of x,y air core correctors \((x_{c1}, y_{c1}), (x_{c2}, y_{c2})\) are used. The first set pitches the deviant incoming beam to read zero on BPM1, and the second corrects the angle at BPM1 to read zero at BPM2.

In practice, we use the same method as in E-FOK. As an example, I illustrate using the y coordinate:

\[
\begin{pmatrix}
\Delta y_1 \\
\Delta y_2
\end{pmatrix} = \begin{pmatrix}
1 & 0 \\
2x2 & 1
\end{pmatrix} \begin{pmatrix}
\Delta \phi_1 \\
\Delta \phi_2
\end{pmatrix} \tag{1}
\]

\{ deviations \} \{ matrix of \} \{ cors angles \}
\{ on BPMs 1,2 \} \{ R_{34} cors BPMs \}

Inverting \( M \) then

\[
\begin{pmatrix}
\Delta \phi_1 \\
\Delta \phi_2
\end{pmatrix} = -\begin{pmatrix}
M^{-1} \\
2x2
\end{pmatrix} \begin{pmatrix}
\Delta y_1 \\
\Delta y_2
\end{pmatrix} \tag{2}
\]

Giving the required corrector angles to zero both BPMs.

**Errors:**

We express all errors at the BPMs. There are two terms, the intrinsic BPM error and the effect of the current regulation of the
CORRECTORS TRANSLATED TO THE BPMs USING EQUATION I

RESULT: \( \pm 1 \mu \) AT BPM1, \( \pm 4 \mu \) AT BPM2

THE INTRINSIC ERROR IN THE BPMs \( \approx \pm 6 \mu \).

ADDING THE TWO IN QUADRATURE

\[ \sigma(BPM1) = \pm 6 \mu \; ; \; \sigma(BPM2) = \pm 7 \mu \]

THE ERROR IN POSITION AT FFTB INPUT IS SIMPLY

THE ERROR IN BPM2 = \( \pm 7 \mu \).

THE ERROR IN ANGLE AT FFTB ENTRANCE IS OBTAINED FROM

THE TWO BPM ERRORS AND DISTANCE BETWEEN THEM (90M)

\[ \Delta \phi = \frac{\sqrt{(6)^2 + (7)^2}}{90} = .1 \mu \]

BOTH THE POSITION AND ANGLE ERRORS EXCEED THE FFTB TOLERANCE (\( \pm 5 \mu \), \( \pm 0.04 \mu \)). HOWEVER, IF WE AVERAGE OVER 10 SHOTS (1 SEC) OF BPM READINGS, THE TOLERANCES ARE MET.
Fig 3.2. Schematic of the 50Line. The launch correctors and BPM's are indicated by boxes.
FFTBLaunch Experiment

Peter Tenenbaum
February 28, 1992

I. Goals and Beam Line
II. Alignment and Steering
III. Hardware Check
IV. Conclusions
V. Future Plans
Goals

1. Get beam on dump -- find out what's needed
2. Measure angle between FFTB and linac
3. Measure misalignments in the launch line; determine whether corrective action needed
4. Test new mover and BPM in beam line:
   --> BPM scale factors (R_{12}'s, mover data)
   --> Reproducibility/linearity of mover vs BPM
   --> BPM resolutions
   --> Other Systematic Errors
Beam Line

--> Equal Emittances (normal Linac running mode)
   \[ \varepsilon_x = \varepsilon_y = 3 \times 10^{-10} \text{ meter-radians} \]

--> All optical elements after linac off

--> Electrons only, 10 Hz, 0.8-1.0 \times 10^{10} \text{ e}\text{-/pulse}
**FFTb Launch**

- **Refrigerated Baffle**
  - Q01, BPM 4001
  - XCOR 9, YCOR 10
  - 50 PO (0.320 in. diam.)
  - 40 B1
  - XCOR 26, YCOR 27
  - 50 Q2, BPM 29
  - 50 PO (0.225 in. diam.)
  - XCOR 34, YCOR 35
  - XCOR 36, YCOR 37
  - 50 O3, BPM 39
  - 50 B1
  - 50 PR2
  - BPM 51
  - PR 1
  - PC-2, IC 2A, 2B (0.8 in. diam.)
  - XCOR 96
  - BPM 20
  - YCOR 97

- **DUMP D-10** (1.625 in. diam.)
  - PC0, IC0GABB (0.8 in. diam.)
  - B1
  - IV 4
  - Q0, BPM 1010
  - Q2
  - Q0, BPM 1020

- **IC104A68**
  - ST60
  - BT61
  - IC68
  - O162

- **Installation**
  - Check alignment
  - "Vertical slice" thru system
1,2. Beam to Dump/Angle Measurement

Required degaussing 50B1 in Beam Switch Yard

Also had to switch off B2 magnets (first magnets in SLC Arcs)

Got Beam on dump using only Linac correctors, 1 in each plane

X angle: 30 ± 3 micro radians to south
Y angle: approx. 0.5 micro radians down

Possible contribution from stray fields in BSY;

However

In nominal Run Mode, this correction produces negligible dispersion at FP
3. 50-line Misalignment

Turned on quads Q1, Q2, and Q3 in 50-line

Re-steered to original orbit using existing 50-line corrector magnets

Quad Misalignments w.r.t. Beam:

<table>
<thead>
<tr>
<th>Quad</th>
<th>Δx, μ</th>
<th>Δy, μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>45</td>
<td>-115</td>
</tr>
<tr>
<td>Q2</td>
<td>70</td>
<td>-205</td>
</tr>
<tr>
<td>Q3</td>
<td>253</td>
<td>-113</td>
</tr>
</tbody>
</table>

All within calculated tolerances (300 microns);
No realignment needed.
4. Hardware Check

BPM Scale Factors -- measured 2 ways:

1. Sweep A3D, A4D correctors over full range (approx \pm 10 micro radians), measure $R_{12}$'s

2. Compare mover LVDT with BPM data, moving Q5 mover 0->+1mm (x), 0->+1.5mm (y) (take buffered data at each mover excursion)

Results:

**X Plane:** corrector sweep: $1.77 \pm 0.02$
mover/BPM test: $1.75 \pm 0.007$

Unresolved systematic errors still exist at 3-5% level

**Y Plane:** corrector sweep: $1.65 \pm 0.02$
mover/BPM test: $1.48 \pm 0.03$

Serious systematic problem with the y-data!!
A vs Q6Y

Y = AX + B
A = 100.4
B = -0.8118

STD DEV = 1.143
STD DEV = 1.4759E-02

RMS FIT ERROR = 3.7485E-02
Chi-square = 0.9240

YCOR CA11 97 BACT (50A40Y)
YCOR CA11 97 BDES (80A40Y) STRT= -.0190 STEPS= 6 SIZE= 780-5

4-FEB-92 01:51:54
Plot of Y mover vs Y BPM, after subtraction
R12/R34 -- Measured vs. Expected (true scale)
Reproducibility/Linearity of mover vs BPM

Examined residuals of linear fit (x only)

Results

Measurement dominated by 3μ angular drift; on this scale, no nonlinearity detectable; no "hysteresis" detectable
BPM Resolutions

At each mover run, took/saved 220 shots of data in Q5 and Q6 BPMs

Measured BPM resolution = standard deviation of Q5-Q6, shot-to-shot

Results

**X Plane**: BPM $\sigma = 5.6 \mu$, consistent with 5$\mu$ resolution and 1$\mu$ angular jitter

**Y Plane**: BPM $\sigma = 30 \mu$, increasing to 250$\mu$
BPM resolution from y data vs mover run

Resolution, microns

Mover run number
Other Systematic Errors

--> Y scale factors inconsistent with X scale factor, and each other

--> "Fliers" of several hundred μ in Y mover data (last 3 runs)

--> BPM resolution in Y worse than expected by factor of 6, increasing to factor of 50 (last 3 mover runs)

Most Likely Culprit: BPMs

BPM TMIT (current) correlations also suggest this
\[ b = -0.6833 \]

\[ \text{EYB REV} = 1.5 \times 10^{-3} \]

\[ \text{RMS FIT ERROR} = 1.363 \times 10^{-2} \]

**STEP VARIABLE = ZERO**

4-FEB-02 01:24:23
\[ b = -9.8693E-03 \]

\[ \text{STD DEV} = 5.1138E-02 \]

\[ \text{RMS FIT ERROR} = 1.0787E-02 \]

**STEP VARIABLE = ZERO**
$x=0, y=1500\mu\text{m}$

$q_{by} \text{ vs } q_{by}$, true scale.
BPM resolution from fixed y data vs mover run

![Graph showing BPM resolution vs mover run number. The y-axis represents resolution in microns, and the x-axis represents mover run number. The data points are marked with error bars.]
Conclusions

-- We can get the beam into the FFTB from linac; launch angle is within tolerances.

--> 50-line quads are aligned to within ±200 microns; no alignment necessary for FFTB.

--> BPM scale factor measured, internal agreement is on 5% level, consistent with test stand results.

--> Mover is reproducible and linear within 3 micron accuracy of measurement, in x.

--> BPM resolution of ~5 microns in x with present electronics (expect 1 micron with final setup).

--> Unresolved systematic error in y data. Evidence points to some form of crosstalk in Q6 BPM, appears in Q5 BPM at large vertical excursions. Some form of spray hitting BPM also possible.
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--> BPM resolution of ~5 microns in x with present electronics (expect 1 micron with final setup).

--> Unresolved systematic error in y data. Evidence points to some form of crosstalk in Q6 BPM, appears in Q5 BPM at large vertical excursions. Some form of spray hitting BPM also possible.
Future Plans

--> Check mechanicals (inc. cables) and electronics for source of y-data error;

--> Turn off/degauss 50B1 and 51/52 B2 magnets and manually measure residual fields;

--> Re-measure alignments with positrons;

--> Repeat corrector/mover/BPM experiment:
    Get statistics on $R_{12}$'s (look for systematics)
    Use Sector 30 Collimators to clean up beam
    Examine fine structure of scale factor and BPM resolution
    Attempt to reproduce y-data fault, if needed.