Sources of Nano-beams – a comparison between ATF, TESLA and NLC Damping Rings

A. Wolski (LBL), W. Decking (DESY) & ATF Group (KEK)

Sources of vertical emittance
Emittance tuning
Global and local Collective effects

Wednesday, June 26, 2002
## Ring Parameters

<table>
<thead>
<tr>
<th></th>
<th>ATF achieved</th>
<th>TESLA e⁺ Ring</th>
<th>NLC MDR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>1.3 GeV</td>
<td>5.0 GeV</td>
<td>1.98 GeV</td>
</tr>
<tr>
<td><strong>Relativistic Factor</strong></td>
<td>2544</td>
<td>9785</td>
<td>3875</td>
</tr>
<tr>
<td><strong>Store Time</strong></td>
<td>200 ms</td>
<td>25 ms</td>
<td></td>
</tr>
<tr>
<td><strong>Damping Time</strong></td>
<td>10/12 ms</td>
<td>28.0 ms</td>
<td>5.00 ms</td>
</tr>
<tr>
<td><strong>Normalized Injected Emittance</strong></td>
<td>100 µm rad</td>
<td>0.01 m rad</td>
<td>150 µm rad</td>
</tr>
<tr>
<td><strong>Normalized Extracted Emittance</strong></td>
<td>0.02 µm rad</td>
<td>0.02 µm rad</td>
<td>0.02 µm rad</td>
</tr>
<tr>
<td><strong>Normalized Equilibrium Emittance</strong></td>
<td>0.038 (0.02) µm rad</td>
<td>0.0138 µm rad</td>
<td>0.0132 µm rad</td>
</tr>
<tr>
<td><strong>Geometric Equilibrium Emittance</strong></td>
<td>15 (7.5) pm rad</td>
<td>1.41 pm rad</td>
<td>3.40 pm rad</td>
</tr>
</tbody>
</table>

ATF results – single bunch

*(low I result)*

ATF needs about a factor ~3 to achieve LC goals
Damping ring comparison

Geometric emittances vs $E$ for LC DR’s
(J. Jowett – PAC01)

$z$, $x$, $y$ emittance vs time –
2 CLIC DR designs
(dashed – low I – no IBS)

CLIC Damping ring studies –
showing importance of IBS
for DR designs

2 GeV ring (similar to NLC design)

4.6 GeV ring (~2.5 km)
Salient features

- **Tesla**
  - 90% damping from wiggler
  - Non-planar
  - Very long straight sections
  - Skew quads for coupling insertion
- **NLC**
  - 60% damping from wiggler
- **ATF**
  - Wiggler usually not used
  - Low energy (1.3 GeV)
  - *exists*
Due to the opening angle ‘geometric part’ of synchrotron radiation

- TESLA 0.42 pm-rad
- NLC 0.14 pm-rad
- ATF (similar to NLC)

- Minimum achieved at ATF 5 pm – rad at low current

\[
\varepsilon_{y,\text{min}} = \frac{C_q \langle \beta_y \rangle I_3}{2J_y I_2}
\]
ATF emittance chronology

- 1997 50 pm-rad
- 1998 35 pm-rad
- 1999 35 pm rad
- 2000 15 pm rad (low I)/ 23 pm rad (nom I)
- 2001 10 pm rad (low I) / 17 pm rad (nom I)
- 2002 <10 pm rad (low I)
Sensitivity estimates for vertical COD, $\eta_y$

For uncorrelated misalignments:

$$\langle y^2_{co} \rangle \approx \frac{\langle \beta_y \rangle}{8 \sin^2 \pi \nu_y} \left( \sum_{\text{quadrupoles}} \beta_y (k_1 l)^2 \right) \langle \Delta Y^2_{\text{quadrupole}} \rangle$$

$$\langle \eta^2_y \rangle \approx \frac{\langle \beta_y \rangle}{2 \sin^2 \pi \nu_y} \left( \sum_{\text{quadrupoles}} \beta_y (k_1 l \eta_x)^2 \right) \langle \Delta \Theta^2_{\text{quadrupole}} \rangle$$

$$\langle \eta^2_y \rangle \approx \frac{\langle \beta_y \rangle}{8 \sin^2 \pi \nu_y} \left( \sum_{\text{quadrupoles}} \beta_y (k_2 l \eta_x)^2 \right) \langle \Delta Y^2_{\text{sextupole}} \rangle$$

Work in progress $\rightarrow$ use only as a rough guide
### Sensitivity Parameters

<table>
<thead>
<tr>
<th></th>
<th>ATF</th>
<th>TESLA e+ Ring</th>
<th>NLC MDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Tune (v_y)</td>
<td>8.7589</td>
<td>41.1915</td>
<td>11.1357</td>
</tr>
<tr>
<td>Mean Beta Function at BPMs</td>
<td>(\left\langle \beta_y \right\rangle)</td>
<td>4.6 m</td>
<td>12 m</td>
</tr>
<tr>
<td>Quadrupole Orbit Factor</td>
<td>(\sum_{\text{quadrupoles}} \beta_y (k_1l)^2)</td>
<td>338 m(^{-1})</td>
<td>563 m(^{-1})</td>
</tr>
<tr>
<td>Quadrupole Dispersion Factor</td>
<td>(\sum_{\text{quadrupoles}} \beta_y (k_1l\eta_x)^2)</td>
<td>2.88 m</td>
<td>82.6 m</td>
</tr>
<tr>
<td>Sextupole Dispersion Factor</td>
<td>(\sum_{\text{sextupoles}} \beta_y (k_2l\eta_x)^2)</td>
<td>486 m(^{-1})</td>
<td>4250 m(^{-1})</td>
</tr>
</tbody>
</table>

**Comparison** *ATF, TESLA, NLC*

Marc Ross – SLAC
Generation of vertical dispersion

<table>
<thead>
<tr>
<th>Lattice</th>
<th>$\sqrt{\langle \eta_y^2 \rangle} / \sqrt{\langle \Theta^2 \rangle_{\text{quadrupole}}}</th>
<th>$\sqrt{\langle \eta_y^2 \rangle} / \sqrt{\langle \Delta Y^2 \rangle_{\text{sextupole}}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATF</td>
<td>6 m</td>
<td>130</td>
</tr>
<tr>
<td>TESLA</td>
<td>40 m</td>
<td>140</td>
</tr>
<tr>
<td>NLC</td>
<td>9 m</td>
<td>100</td>
</tr>
</tbody>
</table>
emittance increment/rms dispersion

\[ \varepsilon_y = 2J \varepsilon \left( \frac{\eta^2_y}{\beta_y} \right) \sigma_\delta \]

<table>
<thead>
<tr>
<th>Lattice and region of energy loss</th>
<th>( \varepsilon_y / \left\langle \eta^2_y \right\rangle )</th>
<th>max ( \sigma_{\eta_y} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATF arcs</td>
<td>2.7\times10^{-7} m^{-1}</td>
<td></td>
</tr>
<tr>
<td>TESLA wiggler</td>
<td>5.6\times10^{-7} m^{-1}</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>NLC full lattice</td>
<td>4.6\times10^{-7} m^{-1}</td>
<td>3.5 mm</td>
</tr>
</tbody>
</table>

- Since dispersion correction to better than 1 mm is generally required, and energy variation is limited to the order of 0.1\%, the BPM resolution must be 1 \( \mu \)m or better.

Comparison \textit{ATF, TESLA, NLC}
Marc Ross – \textit{SLAC}
Emittance generated by $\eta_y$
Comparison of analytic estimates of alignment sensitivities and results of simulations

<table>
<thead>
<tr>
<th></th>
<th>TESLA e⁺ Ring</th>
<th>NLC MDR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytic</td>
<td>Simulation</td>
</tr>
<tr>
<td>Vertical Emittance</td>
<td>$\varepsilon_y / \langle \eta_y^2 \rangle$</td>
<td>$5.63 \times 10^{-7}$ m⁻¹</td>
</tr>
<tr>
<td>Quadrupole Vertical Alignment</td>
<td>$\sqrt{\langle Y_{co}^2 \rangle / \langle \Delta Y^2 \rangle}$</td>
<td>112</td>
</tr>
<tr>
<td>Quadrupole Roll</td>
<td>$\sqrt{\langle \eta_y^2 \rangle / \langle \Delta \Theta^2 \rangle}$</td>
<td>86.0 m</td>
</tr>
<tr>
<td>Sextupole Vertical Alignment</td>
<td>$\sqrt{\langle \eta_y^2 \rangle / \langle \Delta Y^2 \rangle}$</td>
<td>309</td>
</tr>
</tbody>
</table>

The quadrupole vertical alignment, is of limited significance for the vertical emittance, since the uncorrected closed orbit is typically dominated by the principal betatron modes, and the beam offset in the sextupoles is correlated around the ring as a result.
ATF simulated emittance vs sextupole offsets

![Graph showing ATF Sextupole Alignment Sensitivity with the equation y = 0.0036x^2 - 0.0178x]
Emittance Tuning

- Dependence on beam based alignment strategy and systematic errors
  - BPMs and BPM location; local lattice
- BBA consists of two pieces
  1. Determination of BPM / magnet center offset
  2. Determination of component alignment
## Simulation seed distribution/results

<table>
<thead>
<tr>
<th></th>
<th>NLC</th>
<th>TESLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole vertical misalignment rms</td>
<td>100 µm</td>
<td>100 µm</td>
</tr>
<tr>
<td>Quadrupole roll rms</td>
<td>100 µrad</td>
<td>100 µrad</td>
</tr>
<tr>
<td>Sextupole vertical misalignment rms</td>
<td>100 µm</td>
<td>100 µm</td>
</tr>
<tr>
<td>BPM resolution</td>
<td>0.5 µm</td>
<td>1 µm</td>
</tr>
<tr>
<td>Energy variation for dispersion measurement</td>
<td>±0.1%</td>
<td>±0.2%</td>
</tr>
<tr>
<td>Correction effectiveness</td>
<td>90%</td>
<td>70%</td>
</tr>
<tr>
<td>(correction effectiveness w/o coupling bumps)</td>
<td>(85%)</td>
<td></td>
</tr>
</tbody>
</table>

Algorithm development in process
Simulation qualifications

**Included:**
- quadrupole vertical alignment errors;
- quadrupole rotations about the beam axis;
- sextupole vertical alignment errors;
- limited BPM resolution.

**Not included:**
- dipole vertical alignment and rotation errors;
- horizontal orbit and dispersion errors;
- optics errors arising from focusing variations;
- BPM rotations;
- effects of nonlinear wiggler fields;
- limitations from malfunctioning BPMs and correctors;
- tuning of the skew quadrupoles used to implement beam coupling in the TESLA damping ring.
• ATF does not have one BPM/Quad (~ BPM/sextupole)
• The arrangement allows for systematic checks on BBA

• Response matrix techniques not yet tried
  – TESLA response matrix is large compared to existing machines where the technique has been used
ATF BBA resolution requirement

![Graph showing the Sextupole center resolution with different frequencies and vertical emittances. The legend includes symbols for different resolutions: 0 um, 20 um, 40 um, and 60 um. The x-axis represents the vertical emittance in pm-rad, and the y-axis represents the frequency in arb units.](image-url)
BBA (1) Strategies:

- Most involve tedious shunt technique
  - How good is this? / How can we improve?
  - ATF – skew quad/sextupole hysteresis
    - Hysteresis gives residual horizontal kick
- ATF:
  - Strong gradient bend
  - No component movers
- NLC
  - Gradient bend

Comparison ATF, TESLA, NLC
Marc Ross – SLAC
ATF BBA
‘BPM offset’
determination

SF1R.28 Y offset with respect to BPM.83 = -90.63 ± 5.82 um
(fitted slope = 0.00153 ± 1.7849e-005, model slope = 0.92666,)
ATF BBA – basic ‘good’ difference orbit

SF1R.28: Y bump = 800 um, trim = 10 amps
fitted kick = -10.43 ± 0.29 urad (chi2/dof = 1.7026)
Collective effects – IBS & electron cloud

Or: How much ‘global’ tuning is forced?

• tune shifts (from a number of sources) impact the emittance correction algorithms

• practical difficulties separating:
  • emittance growth from collective effects ↔
  • emittance growth resulting from magnet misalignments

Avoid GLOBAL TUNING as much as possible
IBS – an important effect at NLC/ATF

Energy spread on/off $\nu_x = \nu_y$
coupling resonance – showing IBS effect

Comparison ATF, TESLA, NLC
Marc Ross – SLAC
Evidence for IBS at ATF – vertical coupling into $\sigma_E$

Evolution of energy spread following injection for $I$:
1.6e9  4.8e9  8.0e9  
0.6    1.7    2.8 mA

Sequence:
- Vertical still large – no effect on $x$ and $E$
- Vertical damped – increase in $x$ and $E$
- minimum at 70ms ($2.5 \tau_{rad}$)

Simulation consistent when coupling $\rightarrow$

$\varepsilon_y / \varepsilon_x = 0.006$

Nominal extraction time for NLC DR – IBS growth $< equilibrium$
**IBS – relative y/x growth rate**

\[
H = \left[ \eta^2 + (\beta \eta' + \alpha \eta)^2 \right] / \beta
\]

 dispersion invariant

\[
\frac{\mathcal{E}_{y0}}{\mathcal{E}_{x0}} = \frac{\langle H_y \rangle_B}{\langle H_x \rangle_B} \frac{J_x}{J_y}
\]

Zero current emittance – determined by SR in bends

\[
\frac{d \mathcal{E}_y}{d \mathcal{E}_x} = \frac{\langle H_y \rangle}{\langle H_x \rangle} \frac{J_x}{J_y}
\]

Emittance growth from IBS – determined by dispersion throughout

for emittance generated through residual \( \eta \) as opposed to residual coupling

Divide and assume that there is nothing special about \( \eta_y \) in the bends

\[
\langle H_y \rangle_B \approx \langle H_y \rangle
\]

\[
\frac{\langle H_x \rangle_{\text{bends}}}{\langle H_x \rangle} = \frac{(\mathcal{E}_y - \mathcal{E}_{y0})}{\mathcal{E}_{y0}} / \frac{(\mathcal{E}_x - \mathcal{E}_{x0})}{\mathcal{E}_{x0}}
\]

(Tor & Kubo)
Dispersion invariant – $H$ – for ATF and NLC design

$\frac{\langle H \rangle_{\text{bends}}}{\langle H \rangle} = 1.6 @ ATF$

$\frac{\langle H \rangle_{\text{bends}}}{\langle H \rangle} = 0.64 @ NLC$

$H$ at ATF

$H$ of NLC arc cell

NLC DR – A. Wolski (LBL)
Emittance results

- $\varepsilon_{y0}$ extrapolation is poor
- Observed energy spread & horizontal emittance growth indicates a 2 - 3 x smaller vertical emittance than observed
- Growth ratio shows a similar factor
- measurements made 4/00 to 6/01

Table of emittance measurements: ($e^{-9}/e^{-11} x/y$, not normalized)

<table>
<thead>
<tr>
<th></th>
<th>$e_{x0}$</th>
<th>$e_x$</th>
<th>$e_{y0}$</th>
<th>$e_y$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>extracted wires 4/00</td>
<td>1</td>
<td>1.85</td>
<td>1</td>
<td>3</td>
<td>2.35</td>
</tr>
<tr>
<td>extracted Dec-00</td>
<td>1.1</td>
<td>2.2</td>
<td>1.7</td>
<td>4</td>
<td>1.35</td>
</tr>
<tr>
<td>extracted Feb-01</td>
<td>1.1</td>
<td>2.2</td>
<td>0.7</td>
<td>2.8</td>
<td>3.00</td>
</tr>
<tr>
<td>extracted Apr-01</td>
<td>1.1</td>
<td>2.4</td>
<td>1.2</td>
<td>2.5</td>
<td>0.77</td>
</tr>
<tr>
<td>extracted Jun-01</td>
<td>1.2</td>
<td>2.1</td>
<td>0.9</td>
<td>2.3</td>
<td>2</td>
</tr>
<tr>
<td>ring L wire</td>
<td>1.1</td>
<td>2.2</td>
<td>0.7</td>
<td>1.9</td>
<td>1.71</td>
</tr>
</tbody>
</table>

- IBS: $1 < r < 1.6$ (ATF)
- $x/y$ cpl $\eta_y$

\[
r = \frac{(\varepsilon_y - \varepsilon_{y0}) / \varepsilon_{y0}}{(\varepsilon_x - \varepsilon_{x0}) / \varepsilon_{x0}}
\]
Electron cloud density (e+) simulation

Ecloud ~ threshold effect

NLC:
• no magnetic field
• Could be worse in wiggler

Tesla:
• straight only
• Arcs ignored
• Bunch spacing