Accelerator Test Facility – KEK/ATF

Prototype injector for JLC/NLC

ATF is the only test facility with ~NLC emittance
ATF Report

- Single bunch emittance results
  - Evidence for intra-beam scattering
- Emittance measurements
- Single bunch study plans
- Instrumentation RD at ATF
- Multi bunch plans
Emittance

- NLC spec: $\gamma \varepsilon_x$ $3 \times 10^{-6}$ $3 \times 10^{-8}$ m-rad
- ATF achieved: $5 \times 10^{-6}$ $6 \times 10^{-8}$ ($5 \times 10^{-6}$ $<1 \times 10^{-8}$ expected)

- Single bunch; 1.28 GeV; 1e10 ppb (NLC: 1.98 GeV; 8e9)

- What are important emittance effects?
  - ring dispersion / coupling correction
  - intra-beam scattering
  - extraction line optical aberration correction
  - instrument validity
Collective effects – single bunch

- cause either coherent instability or incoherent emittance growth
  - Potential well distortion
  - “Microwave” instability
    - serious problem at SLC
      - worse with ‘strong’ but still a problem with ‘weak’
      - definite threshold observed
  - Intra-beam scattering
    - Key topic of ATF work
    - more studied at proton machines
    - important single bunch emittance driver for NLC
    - no threshold: dependence on bunch volume
Intra-beam scattering

- Similar to synchrotron radiation →
  - growth rate = damping rate at equilibrium
  - collisions involve energy exchange between particles
  - beam temperature in rest frame: 7000:35:1 (x, y, z)
  - SR from bends only; IBS everywhere

\[
\frac{\langle H \rangle_{\text{bends}}}{\langle H \rangle} = 1.6 = \frac{(\varepsilon_y - \varepsilon_{y0}) / \varepsilon_{y0}}{(\varepsilon_x - \varepsilon_{x0}) / \varepsilon_{x0}} \quad \text{(at ATF)}
\]

- (for emittance generated through residual dispersion vν coupling)
  - \( H \) is the dispersion invariant

\[
H = \left[ \eta^2 + (\beta \eta' + \alpha \eta)^2 \right] / \beta
\]
Intra-beam scattering – theory

- small transfer approx. of Touschek lifetime
  - limitation in SR sources

- Bjorken&Mtingwa + Piwinski
  - $x - y$ coupling and microwave related $\sigma_z$ distortion not included in most simulations

- Magnitude
  - overall scale factor usually used (protons…, ALS)

- Tail generation – (should be important for downstream users)
  - cut-off parameter introduced
    - reduces computed ‘rms’ emittance by 30%
$H$ – dispersion invariant for ATF and NLC design

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

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

$H$ at ATF

$H$ of NLC arc cell
Evidence for IBS – vertical coupling into $\sigma_E$

- Vertical still large – no effect on $x$ and $E$
- Vertical damped – increase in $x$ and $E$
- Minimum at 70ms

Simulation consistent when coupling $\rightarrow$

$\varepsilon_y / \varepsilon_x = 0.005$
Energy spread

- Zero current energy spread ~ 5.5e-4 is close to expected.

ε_y / ε_x ≤ 0.002
Energy spread on/off difference coupling resonance – showing IBS effect

Energy spread in extraction line on/off coupling resonance

\[ \sigma_s \text{ [10}^{-4}] \]

- **On Resonance**
  - \( V_c = 300 \text{kV} \)
  - I [mA]

- **Off Resonance**
  - \( V_c = 300 \text{kV} \)
  - I [mA]
Emittance vs intensity

- Extraction line wire scanner emittance
- Simulation uses zero current $\varepsilon_x$

$\varepsilon_y / \varepsilon_x \leq 0.002$
Emittance results

- Growth ratio is well measured
- $\varepsilon_{y0}$ is poorly understood
- Observed energy spread/ horizontal emittance growth indicates a 6x smaller vertical emittance than observed

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>
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<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>
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<tr>
<td>extracted Apr-01</td>
<td>1</td>
<td>2.4</td>
<td>1.2</td>
<td>2.5</td>
<td>0.77</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>

- measurements made 4/00 to 4/01

$$r = \frac{(\varepsilon_y - \varepsilon_{y0}) / \varepsilon_{y0}}{(\varepsilon_x - \varepsilon_{x0}) / \varepsilon_{x0}}$$

- IBS: $1 < r < 1.6$
Constraints on measurement/optical errors from estimate of $r$

- for example – a coupled mixture as would be generated by a skew quad
  \[ \varepsilon_{y\text{meas}} = \varepsilon_{y\text{real}} + k\varepsilon_x \]
  \((k \text{ independent of } I)\)

- → only makes sense if:
  \[ \frac{\varepsilon_y}{\varepsilon_{y0}} < \frac{\varepsilon_x}{\varepsilon_{x0}} \]

- not so for 00/01 data
Orbit correction/emittance optimization

Simulated vertical emittance after each correction

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>COD</td>
<td>2.28</td>
<td>&lt;1.1E-11 rad-m</td>
</tr>
<tr>
<td></td>
<td>(E-11 rad-m)</td>
<td>20 %</td>
</tr>
<tr>
<td>V COD-dispersion</td>
<td>1.67</td>
<td>51 %</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.58</td>
<td>91 %</td>
</tr>
</tbody>
</table>

Misalignment: as measured

+ random 30 micron offset
+ random 0.3 mrad. rotation

BPM error: offset 300 micron, rotation 0.02 rad.
Ring orbits

- Raw BPM readings
- Energy spread measurement an excellent practical indicator of convergence

\[ \eta_{rms} \approx 3mm \]

5/17/01 NLC MAC
Summary – single bunch
low emittance

- relative growth not explained by aberrations in extraction line
- ring simulation indicates unreasonably small vertical emittance
- ring tuning relies on poorly optimized BPM system
- simulation input somewhat unrealistic

- Plans:
  - complete ring beam based alignment
  - BPM system improvements
    - extraction line (RF dipole mode BPM’s)
    - ring
Single bunch study plans

• ZDR prediction for 2 GeV: ~ 20% growth at 1e10
  – What is the impact of the ATF result on the NLC damping ring design?
• $\varepsilon_{yo}$ is too high
  – coupling and dispersion correction
  – BPM resolution and beam based alignment
  – understanding of low intensity, low emittance instrument resolution
Emittance measurements

- wire scanners - in the extraction line...
  - few micron beam size resolution
  - 2-3 micron beam jitter
  - control of eta to few mm
- laserwire – in the ring…
- energy spread – extraction line optics
- SR monitor (results not included)
Synchrotron radiation interferometer

- measure depth of 2 slit modulation vs slit spacing
  - 6.2 um
  - $\varepsilon_y \sim 1.6 \times 10^{-11}$
  - beats diffraction limit by $\sim 6x$
• Resonant cavity close to focus cut-off
  – uses CW laser
  – cavity gain 300
  – measurement ~ 1 hour
Development of a transition radiation profile monitor - OTR

- some controversy over minimum resolvable beam image
  - achieved 7um (12/00) well beyond purported limit
  - smallest OTR spot imaged to date
- theoretical limit: $\sim \lambda$

- Parameters for ATF OTR (built at SLAC)
  - resolution – 2um
  - field of view – 300 x 200 um (or $\sim 2x$)
  - depth of field – 8 um vertical displacement
  - OK light for normal camera – 5e9 ppb

- Instrumentation RD
• 10 µm σ

• successive images illustrating damage process
Multi-bunch operation

- 20 bunches; typical single bunch Imax ~ 2.5e9 (4x lower than single bunch)
- $\varepsilon_y$ increases 1.5x from 1\textsuperscript{st} to 20\textsuperscript{th} bunch (10e-8 normalized avg.)
- vacuum system to be improved 2001
ATF Operation

• ATF operates 20 weeks/year for a 4 1/3 day block /week
  – ~ 2 wks on/ 2 wks off (end effects are large)
• Users (~ students) get about 1/4 time
  – Effective uptime ~ 55 days/year
• Stability is critical for ~10 pm emittance
• Typical beam sizes are 50 x 8 μm
• BPM resolution single shot is ~15μm
• Beam pulse rate is 1.5 Hz

• Precise measurements require long periods of checking/setup
ATF Plans

- Operation is limited by funds (KEK) and manpower (KEK)
  - ~10 physicists (6 FTE) + 8 grad. students
  - SLAC participation began 1997
    - 1 FTE average by ~ 8 SLAC staff
    - ~100K$
  - Contributions from Japanese universities and BINP/Protvino
  - Minimal involvement from other labs

**ATF is the only LC test facility with capability for transverse beam dynamics studies**
  - collective effects, tolerances, optimization, control, stability, technology…