Feedback On Nano-second Timescales: IP Feedback Simulations

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DESY:
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SLAC:
Steve Smith, Thomas Markiewicz …

CERN:
Daniel Schulte…

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- Requirement for a fast IP beam-based feedback system
- NLC, CLIC Simulations
- NLC Background Calculations
- TESLA Simulations
• ‘Fast’ motion (> few Hz) dominated by cultural noise

• Concern for structures with tolerances at nm level (Final Quads)

From Ground Motion studies by A.Seryi et al. (SLAC)
Relative offsets in final Quads due to fast ground motion leads to beam offsets of several $\delta_y$ (2.7 nm for NLC-H 500 GeV).

Correct using beam-based feedback system near IP or by active mechanical stabilization of Quads or both.
<table>
<thead>
<tr>
<th></th>
<th>NLC-H 500 GeV</th>
<th>TESLA 500 GeV</th>
<th>CLIC 500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles/Bunch x 10^{10}</td>
<td>0.75</td>
<td>2.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Bunches/train</td>
<td>190</td>
<td>2820</td>
<td>154</td>
</tr>
<tr>
<td>Bunch Sep (ns)</td>
<td>1.4</td>
<td>337</td>
<td>0.7</td>
</tr>
<tr>
<td>(x/y) (nm)</td>
<td>245 / 2.7</td>
<td>553 / 5</td>
<td>202 / 2.5</td>
</tr>
<tr>
<td>z (\Omega m)</td>
<td>300</td>
<td>110</td>
<td>30</td>
</tr>
</tbody>
</table>

- IP beam characteristics important to fast feedback system for simulated machines.
Beam-beam EM interactions at IP provide detectable signal.

Beam-beam interactions modelled with GUINEA-PIG.

Kick angle and percentage luminosity loss for different vertical beam offsets shown for NLC & CLIC.
measure deflected bunches with BPM and kick other beam to eliminate vertical offsets at IP

- Feedback loop assesses intra-bunch performance and maintains correction signal to the kicker

- Minimise distance of components from IP to reduce latency
### Stripline BPM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to IP</td>
<td>4.3 m</td>
</tr>
<tr>
<td>Stripline radius</td>
<td>1 cm</td>
</tr>
<tr>
<td>Stripline Width</td>
<td>4.4 mm</td>
</tr>
<tr>
<td>Stripline length</td>
<td>10 cm</td>
</tr>
<tr>
<td>Stripline Impedance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Roundtrip time</td>
<td>0.7 ns</td>
</tr>
</tbody>
</table>

### Stripline Kicker

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to IP</td>
<td>4.3 m</td>
</tr>
<tr>
<td>Stripline radius</td>
<td>6 mm</td>
</tr>
<tr>
<td>Stripline length</td>
<td>75 cm</td>
</tr>
<tr>
<td>Stripline Impedance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Roundtrip time</td>
<td>5 ns</td>
</tr>
<tr>
<td>Azimuthal coverage</td>
<td>120 degrees</td>
</tr>
<tr>
<td>Drive voltage required</td>
<td>250 mV/nm</td>
</tr>
<tr>
<td>Drive Power 100nm correction</td>
<td>12.5 W</td>
</tr>
</tbody>
</table>

- BPM response peak near 714 MHz bunch spacing frequency
- Kicker rise-time represents slowest component
- System Design by Steve Smith (SLAC)
F.O.N.

BPM PROCESSOR

3 ns rise-time

G.R. White:
FEEDBACK PERFORMANCE

Latency ~ 37 ns
KICKER GAIN OPTIMISATION

Luminosity loss as function of gain input and beam offset
• Lower gains gives better performance at smaller offsets, higher gains give better performance at higher offsets

• Vary gain dependent on observed beam conditions
FEEDBACK ENHANCEMENTS

Original FB

FB with Signal Averaging
FEEDBACK ENHANCEMENTS

Original Feedback model

Feedback with signal averaging
• Add pre-feedback look-up linearisation step
Gains chosen automatically based on linearisation of beam-beam kick curve.

Gives good luminosity performance over whole offset region.
• Gains chosen automatically based on linearisation of beam-beam kick curve.

• Luminosity performance for Feedback system same distance from IP as NLC case (4.3m) and closer (1.5m).

G.R. White:
Effect of Angle Offset (NLC)

- Beams get small additional kick if incoming with non-compensated crossing angle, also additional lumi loss

- Effect not addressed with this feedback system - if significant angle offset present, additional feedback system further upstream of IP required

\[ \sigma_y = 27 \text{ rad} \]
• $e^+e^-$ Pairs and $\gamma$s produced in Beam-Beam field at IP
• Interactions with material in the IR produces secondary $e^+e^-$, $\gamma$, and neutron radiation
• Study background encountered in Vertex and tracking detectors with and without FB system and background in FB system itself
• Use GEANT3 for EM radiation and Fluka99 for neutrons
Absorption of secondary emission in BPM striplines source of noise in Feedback system

System sensitive at level of about 3 pm per electron knocked off striplines

Hence, significant noise introduced if imbalanced intercepted spray at the level of $10^5$ particles per bunch exists

GEANT simulations suggest this level of imbalance does not exist at the BPM location $z=4.3m$ for secondary spray originating from pair background

G.R.White:
• Insertion of feedback system at z=4.3 m has no impact on secondary detector backgrounds arising from pair background

• Past studies suggest backgrounds adversely affected only when feedback system installed forward of z=3 m
F.O.N. F.O.N.

**DETECTOR N BACKGROUND**

No significant increase in neutron flux in vertex detector area seen arising from pair background

More statistics being generated

- **Default IR**: $5.5 \pm 0.8 \times 10^9$
- **IR with FB**: $6.6 \pm 1.3 \times 10^9$

( neutrons/cm$^2$/1 MeV n equiv./yr )

Sum Over all Layers:
TESLA SIMULATIONS

- Combine PLACET, MERLIN and GUINEA-PIG codes with Simulink feedback algorithm to produce realistic model of TESLA beam collisions and luminosity spectra.

- PLACET used for simulation of beam dynamics in linac in presence of single and multi-bunch wakefields. (D. Schulte)

- MERLIN code incorporating BDS optics used for simulation of beam transport from end of linac to IP. (N. Walker)

- GUINEA-PIG reads in individual bunch data with $O(10^5)$ particles per bunch. This allows handling of non-gaussian (banana) shaped bunches. (D. Schulte)

- All combined and run in Matlab/Simulink environment.
TESLA IP BEAM PROFILES

- Test production with 100 bunches, offset at $1\,\sigma_y$ through the linac structures and with a 35nm RMS misalignment in the BDS quads.

\[ \Delta\bar{y} = 38.4\,\text{nm} = 7.7\sigma_y \]

\[ \Delta\bar{y}' = 12.0\,\mu\text{rad} = 0.96\sigma_y \]
Detect beam-beam kick with 1 or more BPM’s either side of IP.

Feed signal through digital feedback controller to fast strip-line kickers either side of IP.
• Normalised RMS vertical orbit in TESLA BDS due to 70nm RMS quadrupole vibrations.

• Correct betatron oscillation and therefore IP angle crossing at IP by kicking beam at entrance of FFS (~1000m).

• No significant sources of angle jitter beyond this point as all subsequent quads at same IP phase.
• Place kicker at point with relatively high $\sigma$ function and at IP phase.

• Can correct $\sim 130 \, \hat{\Omega} \text{rad}$ at IP ($>10 \, \hat{\Omega} y'$) with 3x1m kickers.

• BPM at phase $90^0$ downstream from kicker.

• To cancel angular offset at IP to $0.1 \, \hat{\Omega} y'$ level:
  
  • BPM 1: required resolution $\sim 0.7 \, \hat{\Omega} m$, FB latency $\sim 4$ bunches.

  • BPM 2: required resolution $\sim 2 \, \hat{\Omega} m$, FB latency $\sim 10$ bunches.
• **Angle feedback:** Calculate mean $y, y'$ for $e^- e^+$ bunches; pass $y$ on to IP FB; angle feedback simulated by passing $y'$ values through simulated PI controller with appropriate transport matrices.

• **Add 2% RMS kicker error.**
• IP Feedback: BPM signal from GUINEA-PIG output (calculated from full bunch structures), feedback on each beam.
• Resolution of each BPM set to 5μm.
Proportional-Integral (PI) Controller:

\[ u_{PI}(k) = u_P(k) + u_I(k) = K_P e(k) + K_I \sum_{j=0}^{k-1} e(j) \]

Subtract \( u_{PI}(k-1) \) to get recursive algorithm:

\[ u_{PI}(k) = u_{PI}(k-1) + K_P (e(k) - e(k-1)) + K_I e(k-1) \]

2 free parameters: gains \( K_P \) and \( K_I \):

- \( K_P \) provides fast response to error signal.
- \( K_I \) cancels steady-state error.

Iterate simulation to obtain optimum parameters to give fast correction and maintain collisions at 0.1\( \gamma \) level.
- Response of system to 100 test bunches with gaussian charge distributions.
- Angle feedback latency set to 3.4 $\mu$s ( $\sim$ 10 bunches).
Luminosity normalised to max luminosity with zero offset over the test 100 bunches.

Lumi loss stabilised at 1-2% level.

Taking last 20 bunches as representative of rest of 1 TESLA pulse (2820 bunches):

$L/L_0 = 0.9906$
Short-range wakefields caused by bunches travelling through cavities in linac disrupt themselves if not aligned with cavity centre:

- Z-Y plane of typical positron bunch from test 100 bunch production:

- Only small increase in vertical emittance, but large loss in luminosity performance with head-on collisions.

- Change in beam-beam dynamics from gaussian bunches.
Feedback algorithm corrects to zero kick angle - no longer optimal lumi.
• Feedback with banana bunches
• Feedback parameters no longer optimal
FEEDBACK PERFORMANCE

- Lumi performance with banana bunches
- \( \frac{L}{L_0} = 0.6473 \)

G.R. White:
SUMMARY

• Fast Ground motion moving quads near IP major source of luminosity loss at a future linear collider.

• NLC, CLIC fast analogue-based IP beam offset feedback systems recover large percentage of lost lumi.

• Backgrounds for FB system or detector components no problem if FB positioning carefully selected.

• Hardware tests ongoing at NLCTA.

• TESLA FB simulated including effects of banana bunches. Improvements to be made- e.g. investigate possibility of including lumi feedback and improved realism of feedback simulations.