Nanometre-level stabilisation on nanosecond timescales

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About me

Madrid
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Born & raised
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Born & raised  MPhys & DPhil
About me

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Outline

• Introduction
  – Feedback at a linear collider
  – International Linear Collider
  – Feedback on Nanosecond Timescales
• Experimental setup at Accelerator Test Facility
• Beam position monitor signal processing
• Modes of feedback operation
• Results
Introduction

Feedback at a Linear Collider

• Successful collision of bunches at a linear collider is critical
• A fast position feedback system is required

Misaligned beams at interaction point (IP) cause beam-beam deflection
Introduction

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Misaligned beams at interaction point (IP) cause beam-beam deflection
Measure deflection on one of outgoing beams
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Feedback at a Linear Collider

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Misaligned beams at interaction point (IP) cause beam-beam deflection
Measure deflection on one of outgoing beams
Correct orbit of next bunch (correlated to previous bunch due to short bunch spacing)
Introduction

International Linear Collider (ILC)

- Proposed linear electron-positron collider
- Centre-of-mass energy: 250-1000 GeV
- Vertical beamsize: 5.9 nm
- Bunch separation: 554 ns

ILC Technical Design Report
Introduction

Accelerator Test Facility (ATF) at KEK

• Test bed for the International Linear Collider
• Facility located at KEK in Tsukuba, Japan
• Goals:
  – 37 nm vertical spot size at final focus
  – Nanometre level vertical beam stability
Introduction

Accelerator Test Facility (ATF) at KEK

Electron source

90 meters
Introduction

Accelerator Test Facility (ATF) at KEK

Electron source

1.28 GeV linear accelerator

90 meters
Introduction

Accelerator Test Facility (ATF) at KEK

- Electron source
- 1.28 GeV linear accelerator
- Damping ring
- 90 meters
Introduction

Accelerator Test Facility (ATF) at KEK

Final focus
Extraction line

Model interaction point (IP) of a collider

Electron source

1.28 GeV linear accelerator

Damping ring

90 meters
Introduction

Accelerator Test Facility (ATF) at KEK

Feedback system

- Final focus
- Extraction line

Model interaction point (IP) of a collider

Electron source

1.28 GeV linear accelerator

Damping ring

90 meters
Introduction

Accelerator Test Facility (ATF) at KEK

• ATF can be operated with 2-bunch trains in the extraction line and final focus
• The separation of the bunches is ILC-like (tuneable up to ~300 ns)
• Our prototype feedback system:
  – Measures the position of the first bunch
  – Then corrects the path of the second bunch
• Train extraction frequency: ~3 Hz
Introduction

Feedback on Nanosecond Timescales (FONT)

• Low-latency, high-precision feedback system
• We have previously demonstrated a system meeting ILC latency, BPM resolution and beam kick requirements
• We have extended the system for use at ATF
• We aim for nanometre level beam stabilisation
Experimental Setup

- 12 cm long strips
- 12 mm radius
- On x and y mover system
Experimental Setup

- Analogue: latency 15 ns
- Dynamic range of ±500 μm
- Resolution of ~300 nm
Cavity BPM at beam waist

- C-band: 6.4 GHz in y
- Low Q: decay time < 30 ns
- Resolve 2-bunch trains
Experimental Setup

- Analogue, 2-stage downmixer
- Developed by Honda et al.
- Resolution of ~50 nm

Processor for cavity BPM
Experimental Setup

- 9 ADC channels at 357 MHz
- 2 DAC channels at 179 MHz
- Xilinx Virtex 5 FPGA
Experimental Setup

- Made by TMD Technologies
- ±30 A drive current
- 35 ns rise time (90% of peak)
Experimental Setup

- Vertical stripline kicker
- 30 cm long strips for K1 & K2
- 12.5 cm long strips for IPK
Stripline BPM Signal Processing

Processor for stripline BPM
As the bunch travels through the BPM, it induces a bipolar signal on the strips. In the frequency domain, this signal peaks at ~700 MHz.

R. J. Apsimon et al., PRST-AB, 2015
The top and bottom strips are used to measure the vertical beam position. The ‘difference over sum’ of the two signals gives the beam position.
Stripline BPM Signal Processing

The signals from the two strips are subtracted using a 180° hybrid and added using a coupler.
An external 714 MHz local oscillator (LO) downmixes the signals to baseband. The beam position is proportional to $V_\Delta/V_\Sigma$. 

Stripline BPM Signal Processing

simplified schematic
Cavity BPM Signal Processing

Processor for cavity BPM
Cavity BPM Signal Processing

**IPB cavity**
Dipole mode frequency (in y)
~6426 MHz

**Reference cavity**
Monopole mode frequency (in y)
~6426 MHz
Cavity BPM Signal Processing

The IPB and reference cavity signals are downmixed using a common, external 5712 MHz LO.
Cavity BPM Signal Processing

The IPB signal is downmixed using the reference cavity signal as LO. The I and Q output signals at baseband are used to obtain the beam position.
Upstream Feedback

- Coupled-loop feedback system allows correction of both position & angle
- P2 and P3 are used to drive K1 and K2
- Latency: 134 ns
- Effect measured at witness BPM MFB1FF, located 30 meters downstream from P3
Upstream Feedback

**Bunch 1**

<table>
<thead>
<tr>
<th>Component</th>
<th>FB Off Jitter:</th>
<th>FB On Jitter:</th>
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<tbody>
<tr>
<td>P2</td>
<td>$1.80 \pm 0.06 , \mu m$</td>
<td>$1.70 \pm 0.05 , \mu m$</td>
</tr>
<tr>
<td>P3</td>
<td>$1.56 \pm 0.05 , \mu m$</td>
<td>$1.66 \pm 0.05 , \mu m$</td>
</tr>
<tr>
<td>MFB1FF</td>
<td>$29.9 \pm 1.0 , \mu m$</td>
<td>$29.4 \pm 0.9 , \mu m$</td>
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</tbody>
</table>
Upstream Feedback

**Bunch 2**

- **P2**: 
  - FB Off Jitter: $1.74 \pm 0.06 \mu m$
  - FB On Jitter: $0.44 \pm 0.01 \mu m$

- **P3**: 
  - FB Off Jitter: $1.55 \pm 0.05 \mu m$
  - FB On Jitter: $0.61 \pm 0.02 \mu m$

- **MFB1FF**: 
  - FB Off Jitter: $27.5 \pm 0.9 \mu m$
  - FB On Jitter: $8.3 \pm 0.3 \mu m$
Upstream Feedback

**P2**
- **FB Off Correlation:** 96.9 ± 0.3 %
- **FB On Correlation:** -25 ± 4 %

**P3**
- **FB Off Correlation:** 93.3 ± 0.6 %
- **FB On Correlation:** +15 ± 4 %

**MFB1FF**
- **FB Off Correlation:** 98.3 ± 0.2 %
- **FB On Correlation:** -14 ± 4 %
Interaction Point Feedback

- IPB position is used to drive the local kicker IPK
- Latency: 212 ns
- Effect measured at IPB
Interaction Point Feedback

FB Off Jitter:
412 ± 29 nm

FB On Jitter:
389 ± 28 nm
Interaction Point Feedback

FB Off Jitter: 420 ± 30 nm
FB On Jitter: 74 ± 5 nm
Interaction Point Feedback

FB Off Correlation: 98.2 ± 0.4 %
FB On Correlation: −13 ± 10 %
Outlook

Two IP BPMs can be used to stabilise the beam at a location between them.
Conclusions

- Demonstrated low-latency, high-precision, intra-train feedback systems
- Upstream coupled-loop position & angle feedback stabilises beam locally to 600 nm
- IP position feedback reduces jitter to 75 nm
- Future plans involve using 2 IP BPMs to drive IP feedback
Thank you for your attention!

Many thanks to the FONT team and our ATF colleagues
## FONT group

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
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<tbody>
<tr>
<td>Phil Burrows</td>
<td>Project leader</td>
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<td>Rebecca Ramjiawan</td>
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Ground Motion vs. Frequency

Vertical ground motion power spectral density integrated up from a range of cut-off frequencies to give the RMS ground motion as a function of frequency.

R. Amirikas et al., EUROTeV, 2005
Monopole and Dipole Cavity Modes

Monopole mode
\( \text{TM}_{r\phi z} = \text{TM}_{010} \)

Dipole mode
\( \text{TM}_{r\phi z} = \text{TM}_{110} \)

Electric field position independent

Electric field proportional to position

Y. Inoue et al., PRST-AB, 2008
Upstream Feedback

measured

propagated

![Graphs showing measured and propagated data for MFB1FF bunch 2.](image)