Progress towards nanometre beam stabilisation at ATF2

Feedback On Nanosecond Timescales (FONT)

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Now at: *CERN; **UBS

in collaboration with: KEK, KNU, LAL
Outline

• ATF2 project at KEK
• Stripline BPM system
• Coupled-loop $y, y'$ feedback system
• Cavity BPMs and progress towards nm resolution
• Summary + outlook
ATF2/KEK

光陰極型高周波電子銃
Photocathode RF Gun

電子線形加速器(1.3GeV)
S-band electron LINAC

最終収束ビームライン
Nano-meter beam R&D (ATF-FF)

ビーム取り出しライン
Extraction line

ダンピングリング
Damping Ring
# ATF2 design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>1.3</td>
</tr>
<tr>
<td>Intensity (electrons/bunch)</td>
<td>$1 \times 10^{10}$</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>3.12</td>
</tr>
<tr>
<td>Horizontal emittance $\epsilon_x$ (m rad)</td>
<td>$2 \times 10^{-9}$</td>
</tr>
<tr>
<td>Vertical emittance $\epsilon_y$ (m rad)</td>
<td>$1.2 \times 10^{-11}$</td>
</tr>
<tr>
<td>Horizontal IP beam size $\hat{x}^*$ (m)</td>
<td>$2.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>Vertical IP beam size $\hat{y}^*$ (m)</td>
<td>$3.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>Horizontal IP beta function $\beta_x^*$ (m)</td>
<td>$4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Vertical IP beta function $\beta_y^*$ (m)</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>RMS energy spread (%)</td>
<td>0.08</td>
</tr>
</tbody>
</table>
ATF2/KEK: prototype final focus

Goals:
1) 37 nm beam spot (44 nm achieved 2014 – reproducibly)
2) Beam spot stabilisation at nanometre level
ATF2/KEK: prototype final focus

Beam feedback + feed-forward systems
Precision cavity + stripline BPMs
Beam size / emittance diagnostics
Beam tuning techniques …
FONT5 ‘intra-train’ feedbacks
FONT5 ‘intra-train’ feedbacks
Stabilising beam near IP

1. Upstream FB: monitor beam at IP
2. Feed-forward: from upstream BPMs → IP kicker
3. Local IP FB: using IPBPM signal and IP kicker
FB loop schematic

e-

kicker

BPMs

FONT amplifier

BPM electronics

FONT digital FB
Xilinx Virtex5 FPGA

9 ADC input channels
(TI ADS5474)

4 DAC output channels
(AD9744)

Clocked at up to 400 MHz
(phase-locked to beam)
High-power, low-latency amps

CLIC CTF3 phase feed-forward amp

MOPB063
FONT4 drive amplifier

- FONT4 amplifier, outline design done in JAI/Oxford
- Production design + fabrication by TMD Technologies
- Specifications:
  
  +/- 15A (kicker terminated with 50 Ohm)
  +/- 30A (kicker shorted at far end)
  35ns risetime (to 90%)
  pulse length 10 us
  repetition rate 10 Hz
Stripline BPMs
FONT5 stripline BPM system
Stripline BPMs

BPM on x-y mover system (IFIC)
BPM readout

LO source

LO phase shifters

LO signals

P3
P2
P1
stripline BPMs
stripline phase shifters
stripline signals

A3
A2
A1
analogue processor modules
processor output signals

digitizer
BPM signal processing
BPM signal processor
BPM signal processor outputs

(a) $V_A$ (mV)

(b) $V_S$ (mV)
BPM signal processor latency

Bench latency meas:

10ns or 15ns with amplifier stage
BPM signal digitisation

BPM analogue processor outputs

P1: $V_{\Sigma Q}$, $V_\Delta$, $V_\Sigma$

14-bit ADC
- ADC1
- ADC2
- ADC3

FPGA
- ADC4
- ADC5
- ADC6

14-bit DAC
- DAC1
- DAC2

- to feedback kicker amplifiers
- to DAQ

- 357 MHz clock
- trigger
3-bunch train at ATF (proxy for ILC)

Single-shot measurement

![Graph showing a single-shot measurement with a time interval of 154 ns.](image)
BPM system resolution

Resolution = 291 ± 10 nm
(Q ~ 1nC)
Design and performance of a high resolution, low latency stripline beam position monitor system


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(Received 1 October 2014; published 19 March 2015)

A high-resolution, low-latency beam position monitor (BPM) system has been developed for use in particle accelerators and beam lines that operate with trains of particle bunches with bunch separations as low as several tens of nanoseconds, such as future linear electron-positron colliders and free-electron lasers. The system was tested with electron beams in the extraction line of the Accelerator Test Facility at the High Energy Accelerator Research Organization (KEK) in Japan. It consists of three stripline BPMs instrumented with analogue signal-processing electronics and a custom digitizer for logging the data. The design of the analogue processor units is presented in detail, along with measurements of the system performance. The processor latency is $15.6 \pm 0.1$ ns. A single-pass beam position resolution of $291 \pm 10$ nm has been achieved, using a beam with a bunch charge of approximately 1 nC.
Upstream FONT5 System

Analogue Front-end BPM processor

FPGA-based digital processor

Kicker drive amplifier

Beam

Stripline BPM with mover system

Strip-line kicker
Upstream FONT5 System

Analogue Front-end BPM processor

FPGA-based digital processor

Kicker drive amplifier

Beam

Strip-line kicker

Stripline BPM with mover system

Meets ILC requirements: BPM resolution, Dynamic range, Latency
Witness BPM

![Diagram showing Witness BPM with various beam elements labeled such as IP, QD0FF, QF1FF, QF7FF, MFB1FF, QF15X, QD14X, QF13X, QD12X, QF11X, QD10X, QF9X, and P1, K1, P2, and K2. The beam direction is indicated from left to right. Colors represent different types of elements: red for Quadrupole, blue for Sextupole, green for Dipole, yellow for Skew Quadrupole, and gray for Corrector. A Damping Ring is shown at the end of the beam path.]
FONT5 system performance

Bunch 1: input to FB

FB off
FB on
Bunch 1: input to FB
- FB off
- FB on

Bunch 2: corrected
- FB off
- FB on

FONT5 system performance
Time sequence

Bunch 2: corrected

FB off
FB on
### Jitter reduction

<table>
<thead>
<tr>
<th>BPM</th>
<th>Feedback off</th>
<th>Feedback on</th>
<th>Feedback off</th>
<th>Feedback on</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>1.80 ± 0.06</td>
<td>1.70 ± 0.05</td>
<td>1.74 ± 0.06</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>P3</td>
<td>1.56 ± 0.05</td>
<td>1.66 ± 0.05</td>
<td>1.55 ± 0.05</td>
<td>0.61 ± 0.02</td>
</tr>
<tr>
<td>MFB1FF</td>
<td>29.9 ± 1.0</td>
<td>29.4 ± 0.9</td>
<td>27.5 ± 0.9</td>
<td>8.3 ± 0.3</td>
</tr>
</tbody>
</table>

Factor ~ 3.5 improvement
Bunch 1 – bunch 2 correlation

FB off

FB on

<table>
<thead>
<tr>
<th>BPM</th>
<th>Feedback off</th>
<th>Feedback on</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>+96.9 ± 0.3</td>
<td>-25 ± 4</td>
</tr>
<tr>
<td>P3</td>
<td>+93.3 ± 0.6</td>
<td>+15 ± 4</td>
</tr>
<tr>
<td>MFB1FF</td>
<td>+98.3 ± 0.2</td>
<td>-14 ± 4</td>
</tr>
</tbody>
</table>
Feedback loop

(a) P2 bunch 1

(b) P3 bunch 1

(c) MFB1FF bunch 1

(d) P2 bunch 2

(e) P3 bunch 2

(f) MFB1FF bunch 2
Feedback loop

(a) P2 bunch 1

(b) P3 bunch 1

(d) P2 bunch 2

(e) P3 bunch 2

(a) MFB1FF bunch 1

(b) MFB1FF bunch 2
Witness BPM: measure predict
Predicted jitter reduction at IP

\[ y \]

\[ y' \]

\[ \text{FB off} \]

\[ \text{FB on} \]
Predicted jitter reduction at IP

<table>
<thead>
<tr>
<th>Bunch</th>
<th>Position y jitter (nm)</th>
<th>Angle y’ jitter (urad)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feedback off</td>
<td>Feedback on</td>
</tr>
<tr>
<td>1</td>
<td>9.5 ± 0.3</td>
<td>10.1 ± 0.3</td>
</tr>
<tr>
<td>2</td>
<td>9.4 ± 0.3</td>
<td>3.6 ± 0.1</td>
</tr>
</tbody>
</table>

Predict position stabilised at few nanometre level...

How to measure it?!
Cavity BPM system near IP

Quadrupole  Sextupole  Dipole  Skew Quadrupole  Corrector
IP cavity BPM system
## Low-Q cavity BPMs

### Design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dipole cavities</th>
<th>Reference cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x$ port</td>
<td>$y$ port</td>
</tr>
<tr>
<td>Resonant frequency $f_{mn}$ (GHz)</td>
<td>5.712</td>
<td>6.426</td>
</tr>
<tr>
<td>Internal quality factor $(Q_0)_{mn}$</td>
<td>4959</td>
<td>4670</td>
</tr>
<tr>
<td>Decay time $\tau_{mn}$ (ns)</td>
<td>18.72</td>
<td>17.23</td>
</tr>
</tbody>
</table>
Cavity BPM signal processing

\[ I \rightarrow I' \]

\[ Q \rightarrow Q' \]

bunch charge
Cavity BPM outputs (2-bunch train)

Single-shot measurement

![Graphs showing cavity BPM outputs with labels I and Q and a time difference of 204ns.](Image)
Example position calibration: 1)
Example position calibration: 2)
Example position calibration: 3)
• Signal levels $\rightarrow$ saturation $\rightarrow$ non-linear response

• Dynamic range $\leftrightarrow$ resolution

• Operate with (remotely controlled) attenuation

• Optimal resolution (0db) $\rightarrow$
  dynamic range $\pm 3\mu m$ w.r.t. nominal centre

• Beam setup + beam quality are critical
Waveforms at 0db – ugly!

Position information superposed on static artefact

+-1.8um
Mean-subtracted waveforms

\[ \pm 1.8\text{um} \]
BPM response vs. attenuation

Position calibration scale

Graph showing the relationship between absolute calibration constant and variable attenuator setting.
Beam jitter vs. attenuation

Noise floor ~ 30nm
Resolution vs. sample # (0db)

Fitting method

Resolution as function of sample no

Geometric method

Resolution as function of sample no

<table>
<thead>
<tr>
<th>Fitting</th>
<th>Geom</th>
</tr>
</thead>
<tbody>
<tr>
<td>52nm</td>
<td>52nm</td>
</tr>
<tr>
<td></td>
<td>57nm</td>
</tr>
<tr>
<td></td>
<td>54nm</td>
</tr>
</tbody>
</table>
Resolution – integrate samples 3 - 10

IPA Resolution Residuals from Least Squares Fitting

Size of Residuals / μm

μ: -0.00
σ: 0.04

IPB Resolution Residuals from Least Squares Fitting

Size of Residuals / μm

μ: 0.00
σ: 0.04

IPC Resolution Residuals from Least Squares Fitting

Size of Residuals / μm

μ: 0.00
σ: 0.05

Fitting Geom

42nm 42nm 47nm 55nm
Jitter vs. QD0FF setting (waist scan)
Jitter vs. QD0FF setting (waist scan)

Minimum jitter: 49 nm (integration)
Interaction Point FONT System

Analogue Front-end BPM processor

FPGA-based digital processor

Kicker drive amplifier

Latency ~ 160ns

Beam

Cavity BPM

Strip-line kicker
IPFB results

Bunch 1: not corrected, jitter ~ 400nm

Bunch 2: corrected, jitter ~ 67nm

Corrected jitter 67nm → resolution 47nm
IPFB results: time sequence

![Graphs showing position vs. trigger number for IPB (Y) bunch 1 and 2, with Off and On conditions indicated.](image)
IPFB performance vs. QD0FF setting

Prediction based on incoming jitters of bunches 1 and 2 and measured bunch 1-2 correlation, assuming perfect FB
Correcting beams in single-shot mode to sub-micron accuracy is not easy!
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Pushed stripline BPM resolution to ~ 300nm (Q ~ 1 nC)
Correcting beams in single-shot mode to sub-micron accuracy is not easy!

Pushed stripline BPM resolution to ~ 300nm (Q ~ 1 nC)

Intra-train FB system that meets ILC requirements

This system capable of nm-level beam stabilisation
Correcting beams in single-shot mode to sub-micron accuracy is not easy!

Pushed stripline BPM resolution to \( \sim 300\text{nm} \) (\( Q \sim 1\text{ nC} \))

Intra-train FB system that meets ILC requirements

This system capable of nm-level beam stabilisation

Low-Q cavity BPM system operating in multi-bunch mode
Summary

Correcting beams in single-shot mode to sub-micron accuracy is not easy!

Pushed stripline BPM resolution to ~ 300nm (Q ~ 1 nC)

- Intra-train FB system that meets ILC requirements
- This system capable of nm-level beam stabilisation

Low-Q cavity BPM system operating in multi-bunch mode

- Resolution ~ 50 nm
- Closed feedback loop
- Stabilised beam to 67 nm
Summary

Correcting beams in single-shot mode to sub-micron accuracy is not easy!

Pushed stripline BPM resolution to ~ 300nm (Q ~ 1 nC)

- Intra-train FB system that meets ILC requirements
- This system capable of nm-level beam stabilisation

Low-Q cavity BPM system operating in multi-bunch mode

- Resolution ~ 50 nm
- Closed feedback loop
- Stabilised beam to 67 nm

Work ongoing to understand/improve cavity BPM resolution
In 2008 Honda et al used same electronics on higher-Q BPMs, in single-bunch mode, with 3X bunch charge, and obtained resolution ~ 9nm (signal integration + 13-parameter fit)

If we use same technique we obtain resolution ~ 30nm
If we scale for bunch charge naively, resolution → 10nm

We may actually be close to same performance level, but resolution obtained from a 13-parameter fit does not help with real-time input to a feedback system …
FONT Group alumni

- Gavin Nesom: Riverbed Technology, California
- Simon Jolly: UCL faculty
- Steve Molloy: ESS staff
- Christine Clarke: SLAC staff
- Christina Swinson: BNL staff
- Glenn Christian: JAI faculty
- Glen White: SLAC staff
- Tony Hartin: DESY staff
- Ben Constance: CERN Fellow → start-up Cambridge
- Robert Apsimon: CERN Fellow → Cockcroft
- Javier Resta Lopez: Marie Curie Fellow, Cockcroft
- Alex Gerbershagen: PSI postdoc
- Michael Davis: UBS, London
- Doug Bett: CERN Fellow
- Young-Im Kim: IBS Daejon