Performance Of Nanometre-level Resolution Cavity Beam Position Monitors And Their Application In An Intra-train Beam Position Feedback System

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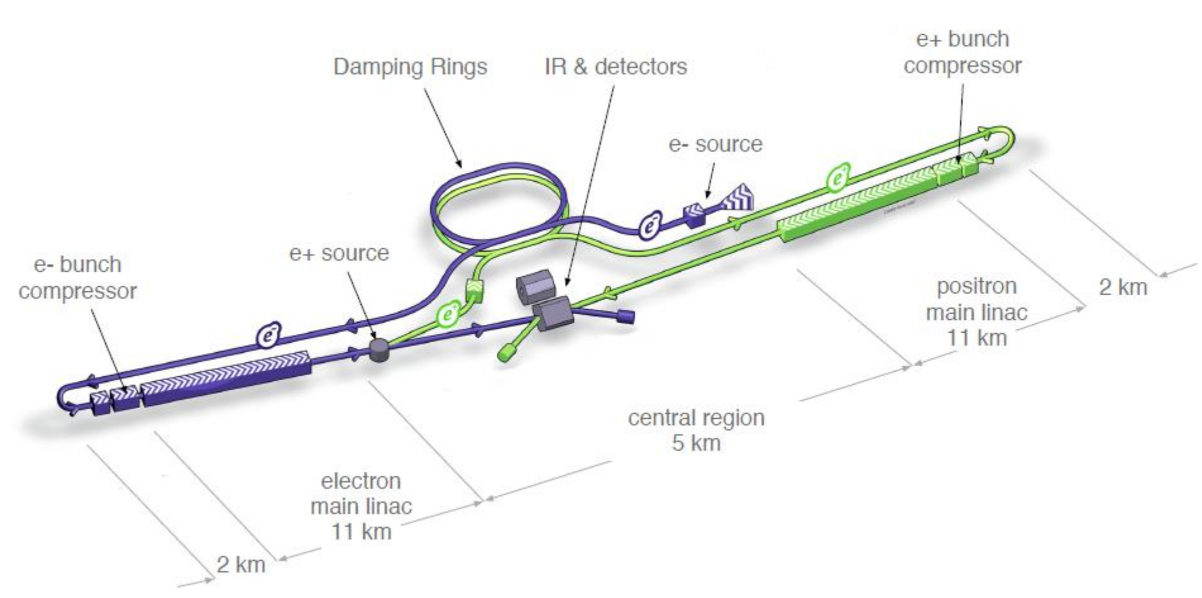
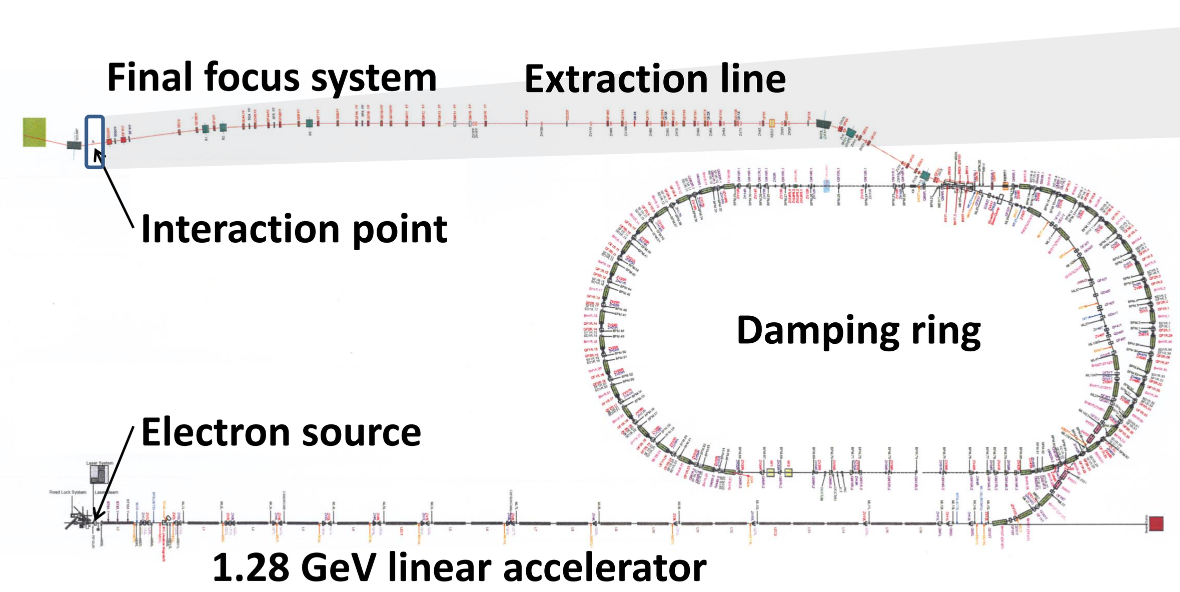
A system of three low-Q cavity beam position monitors (BPMs), installed in the interaction point (IP) region of the Accelerator Test Facility (ATF2) at KEK, has been designed and optimised for nanometre-level beam position resolution. The BPMs have been used to provide an input to a low-latency, intra-train beam position feedback system consisting of a digital feedback board and a custom stripline kicker with power amplifier. The feedback system has been deployed in single-pass, multi-bunch mode with the aim of demonstrating intra-train beam stabilisation on electron bunches of charge ~1 nC separated in time by c. 220 ns. The BPMs have a demonstrated resolution of below 50 nm on using the raw measured vertical positions at the three BPMs, and has been used to stabilise the beam to below the 75 nm level. Further studies have shown that the BPM resolution can be improved to around 10 nm on making use of quadrature-phase signals and the results of the latest beam tests will be presented.

International Linear Collider



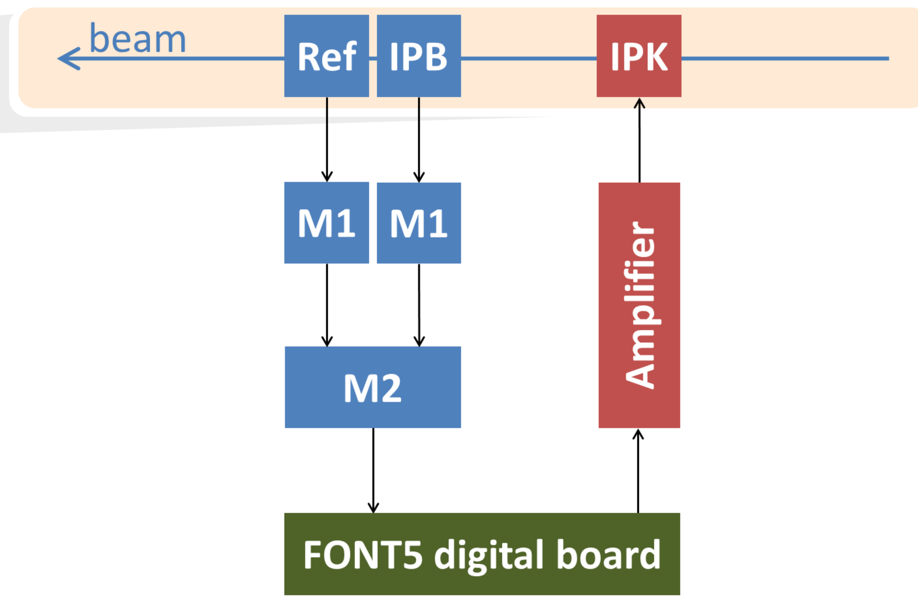
The International Linear Collider (ILC) is a proposed linear electron-positron collider with a centre-of-mass energy of 500 GeV [1]. The schematic above shows the 6.7 km circumference damping rings followed by the 11 km long superconducting main linacs. The ILC is designed to have a vertical beam size at the interaction point (IP) of 5.9 nm and a bunch separation of 554 ns.

Accelerator Test Facility



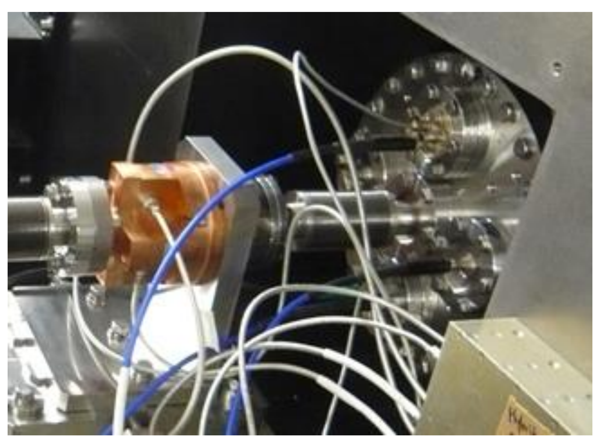
The Accelerator Test Facility (ATF2) at KEK, Tsukuba, Japan is a test bed for the ILC. The ATF2 consists of a 1.28 GeV electron linac, a super-low emittance damping ring and a scaled version of the ILC's final focus system. ATF2's goal is to achieve a 37 nm beam size with nanometre beam stability as measured at the IP [2].

Feedback on Nanosecond Timescales



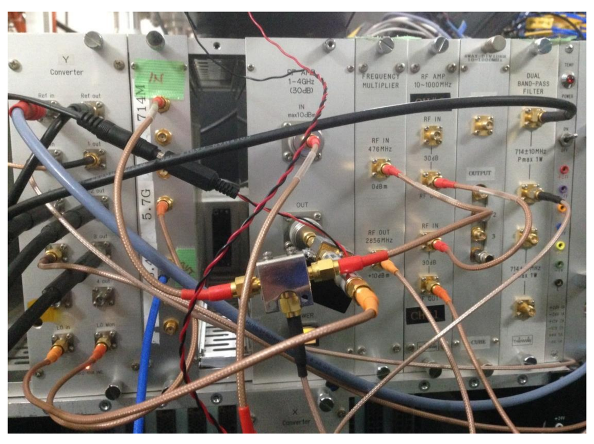
The Feedback on Nanosecond Timescales (FONT) [3] project works towards ATF2's high stability goal by performing intra-train beam-based feedback. Operating with 2-bunch trains at a bunch separation of 215.6 ns, the FONT system uses a beam position monitor (BPM) to measure the path taken by the first bunch in order to then correct the path of the second bunch.

Ref IPB Cavities



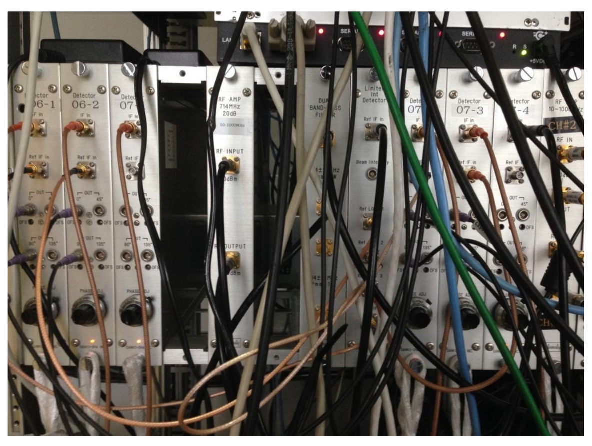
IPB is a C-band cavity BPM on an x, y mover system [4] with a 6.4 GHz dipole mode for the y signal. The reference cavity has a 6.4 GHz monopole mode and is used for phase detection and charge normalisation [5].

M1 M1 Stage 1 mixer



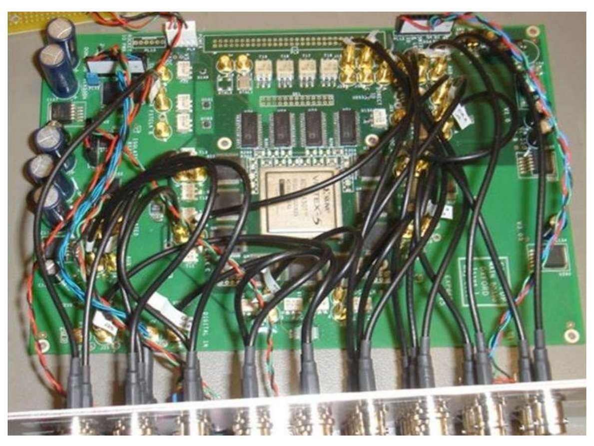
The first stage downmixer takes the 6.4 GHz reference and IPB signals and mixes each with an external common 5.7 GHz local oscillator (LO) to produce downmixed outputs at 714 MHz [6].

M2 Stage 2 mixer



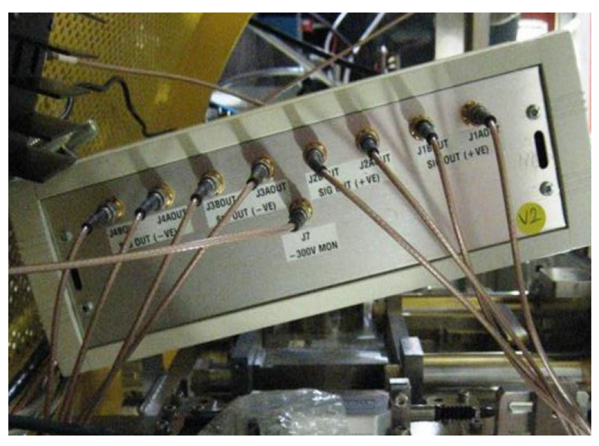
The second stage downmixer mixes the 714 MHz IPB signal using the 714 MHz reference as the LO [6], giving 2 signals at baseband: I (IPB and reference mixed in phase) and Q (mixed in quadrature).

FONT5 digital board



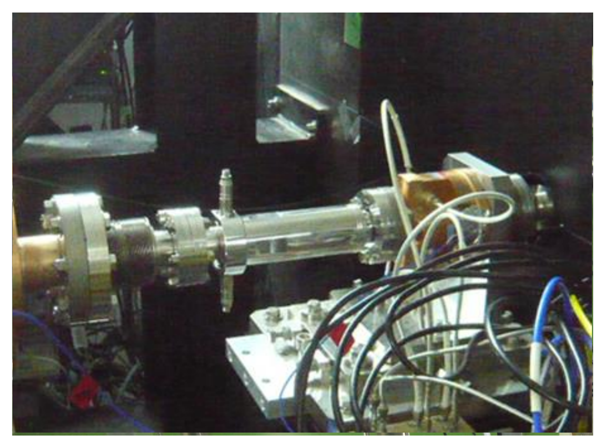
The FONT5 digital board has a Virtex-5 Field Programmable Gate Array (FPGA) [7]. The I, Q and charge (q) signals are digitised at 357 MHz and used to compute the beam position and generate the kick signal.

Amplifier



The kick signal from the FONT5 board is amplified by an amplifier manufactured by TMD technologies [8]. The amplifier provides ±30 A of drive current and takes 35 ns to reach 90 % of peak.

IPK Kicker



The IP stripline kicker consists of a pair of top and bottom electrodes connected to the corresponding amplifier at its downstream end and shorted together at its upstream end, forming a transmission line.

BPM Resolution Results

The BPM resolution of the three BPM system (IPA, IPB and IPC) is estimated by predicting the beam position at IPC from the beam position measurement at IPA and IPB. Two methods are used to predict the position at IPC:

Geometric	$y_{\mathrm{IPC}} = a_1 y_{\mathrm{IPA}} + a_2 y_{\mathrm{IPB}}$ (a_1 and a_2 obtained from transfer matrices)
Fitting	$I'_{\mathrm{IPC}} = c_1 I'_{\mathrm{IPA}} + c_2 I'_{\mathrm{IPB}} + c_3$ ($c_1, c_2, \ldots$ obtained by linear regression)

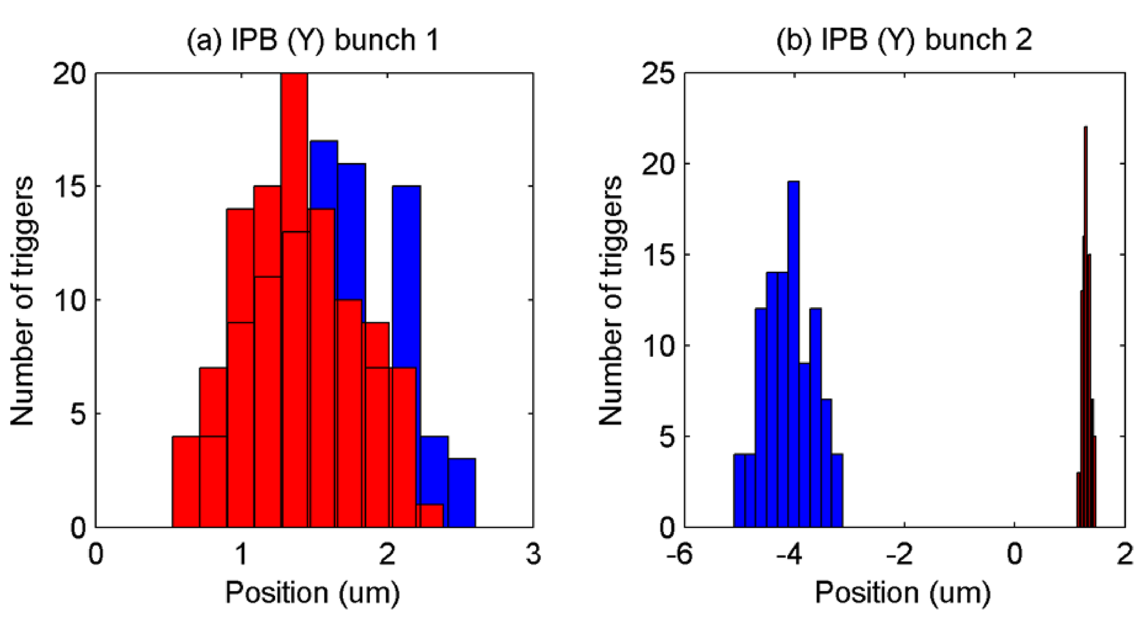
The residual of the measured and predicted positions at IPC is calculated for each pulse, and the standard deviation δ of the residuals is computed. The resolution is then [6]:

$$\text{Resolution} = \frac{\delta}{\sqrt{1 + a_1^2 + a_2^2}}.$$

Method	Resolution (nm)
Geometric	49.5 ± 2.0
Fitting I' & constant	16.4 ± 0.7
Fitting I', Q' & constant	14.1 ± 0.6
Fitting I', Q', q & constant	13.4 ± 0.6

The results show that a base resolution of around 50 nm can be achieved using the geometric method. Transitioning to fitting I' (proportional to beam position) brings the resolution down by a factor 3, and including Q' (orthogonal to I') and q (charge) to the fit brings the resolution down further to the order of 10 nm.

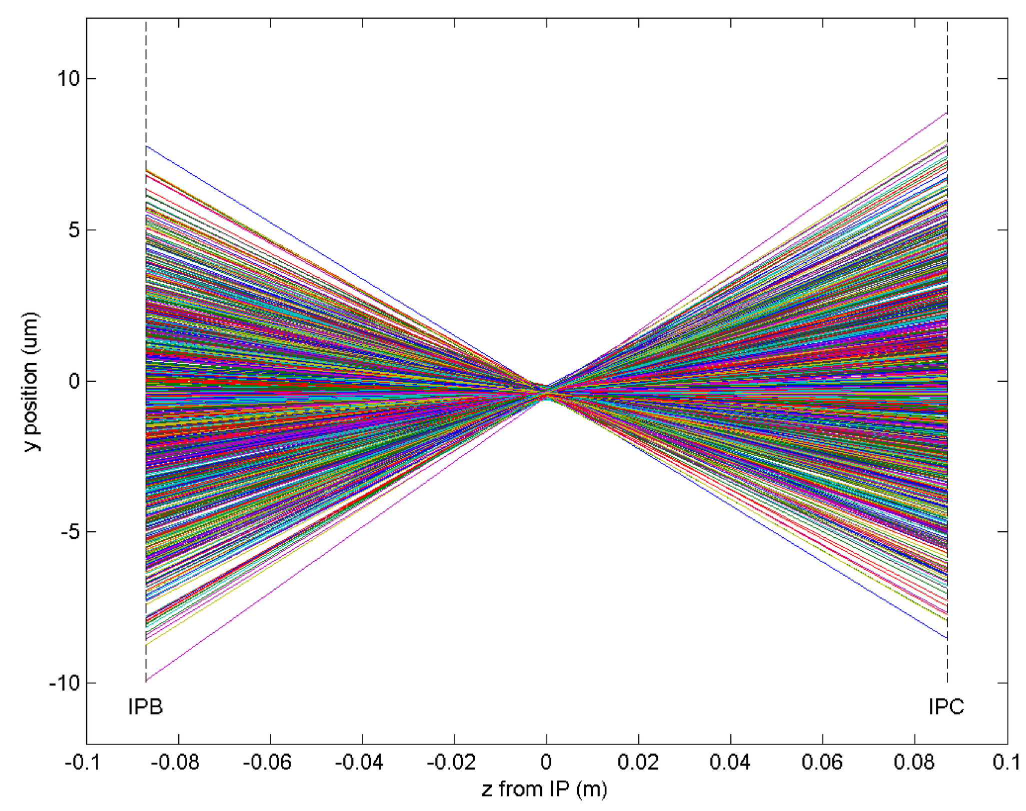
Feedback Results



Feedback	Bunch 1 jitter (nm)	Bunch 2 jitter (nm)
Off	412 ± 29	420 ± 30
On	389 ± 28	74 ± 5

Operation of the feedback system stabilises the position jitter of the second bunch from 420 nm to 74 nm. Given the incoming values for the jitter of the two bunches and the bunch-to-bunch position correlation, the feedback is expected to stabilise the beam jitter to 79.4 nm [9], which agrees with measurement.

Outlook



	Interpolated waist
y jitter (nm)	82
z (mm)	0.3

The use of two BPMs (IPB and IPC) located either side of the IP beam waist, in order to stabilise the beam at the waist, may improve the position resolution available to the feedback system as the error on the interpolated position would be $\sigma_r/\sqrt{2}$ where σ_r is the resolution of either BPM [9].

References

[1] International Linear Collider: www.linearcollider.org/ILC/
[2] Accelerator Test Facility: www-atf.kek.jp/atf/
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[4] O. R. Blanco et al., IPAC2015 proceedings, MOPHA003.
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[7] Xilinx Virtex 5: www.xilinx.com/products/virtex5/
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[9] N. Blaskovic Kraljevic, DPhil thesis, Oxford University, 2015.