Fast Jitter Control and Feedback

Feedback On Nanosecond Timescales (FONT) Group
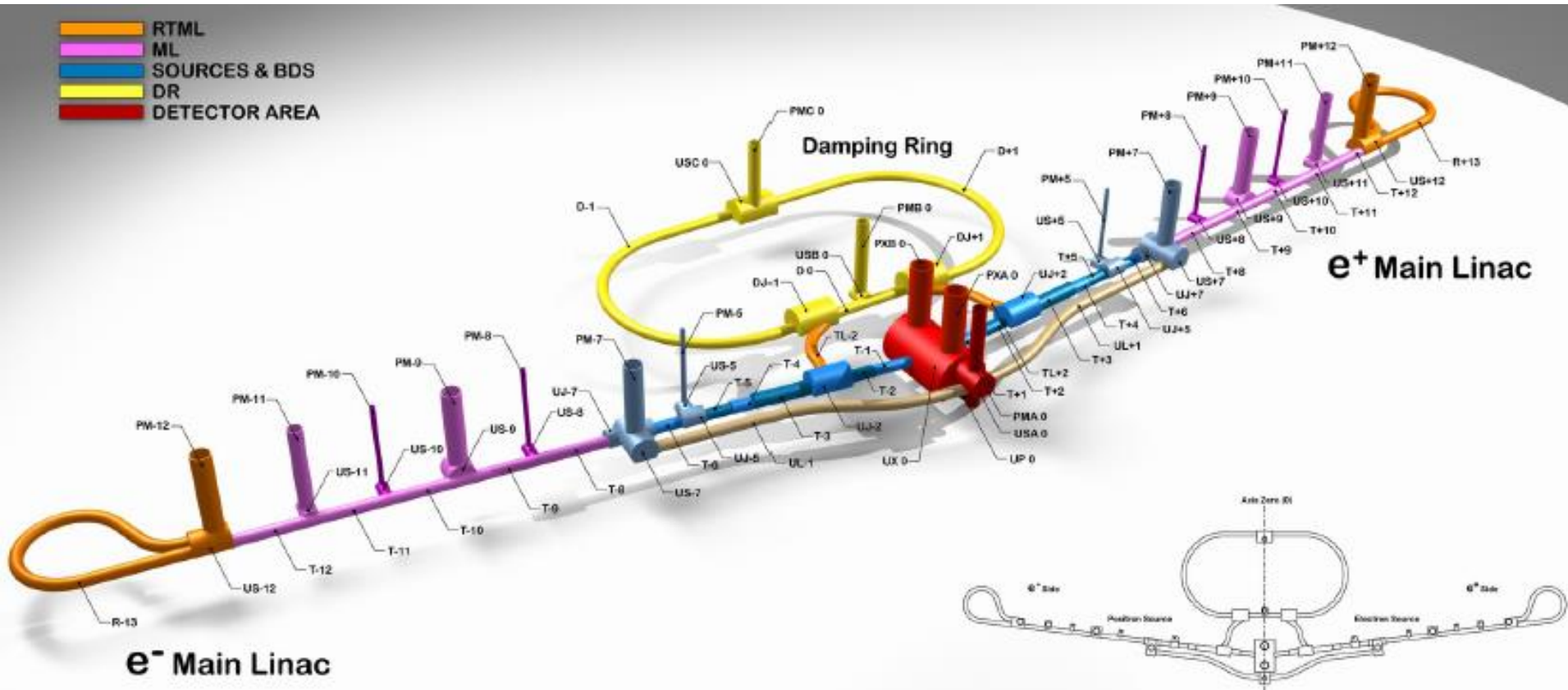
Philip Burrows
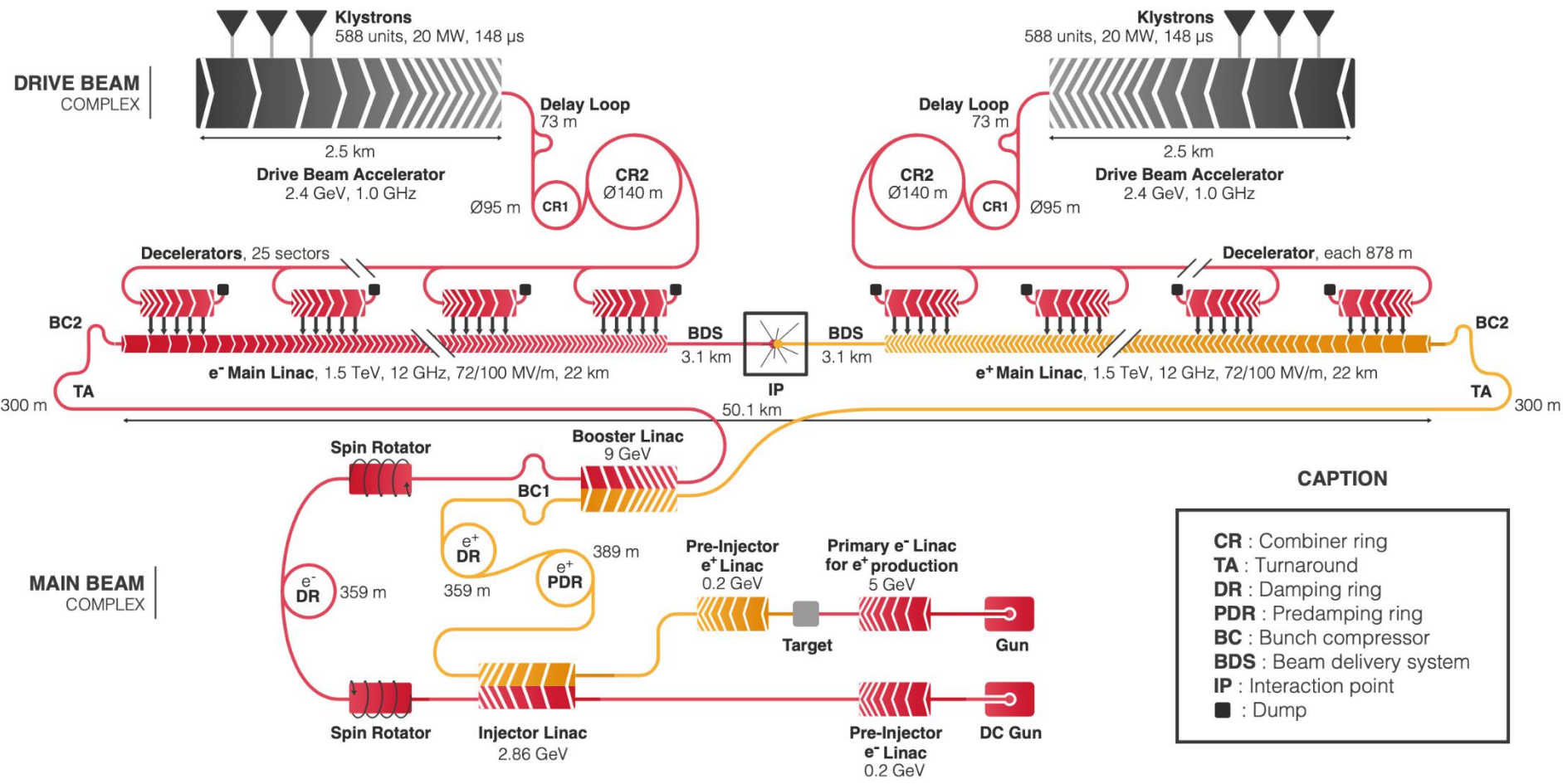
John Adams Institute

Oxford University

Outline

- **Interaction point feedback for ILC + CLIC**
- **FONT prototype systems performance**
- **Applications of FONT technology to jitter control:**
  - **Ground-motion feed-forward**
  - **Phase stability for CLIC drive beam**
  - **Wakefield control at ATF2**
  - **'IP FB' at ATF2**

International Linear Collider

# Compact Linear Collider
3 TeV layout

Beam parameters

	ILC 250	500	CLIC 3 TeV	
Electrons/bunch	2	2	0.37	10**10
Bunches/train	1312	1312	312	
Bunch separation	554	554	0.5	ns
Train length	727	727	0.156	us
Train repetition rate	5	5	50	Hz
Horizontal IP beam size	516	474	40	nm
Vertical IP beam size	8	6	1	nm
Luminosity	1.4	1.8	6	10**34

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Beam-beam deflection (ILC500)
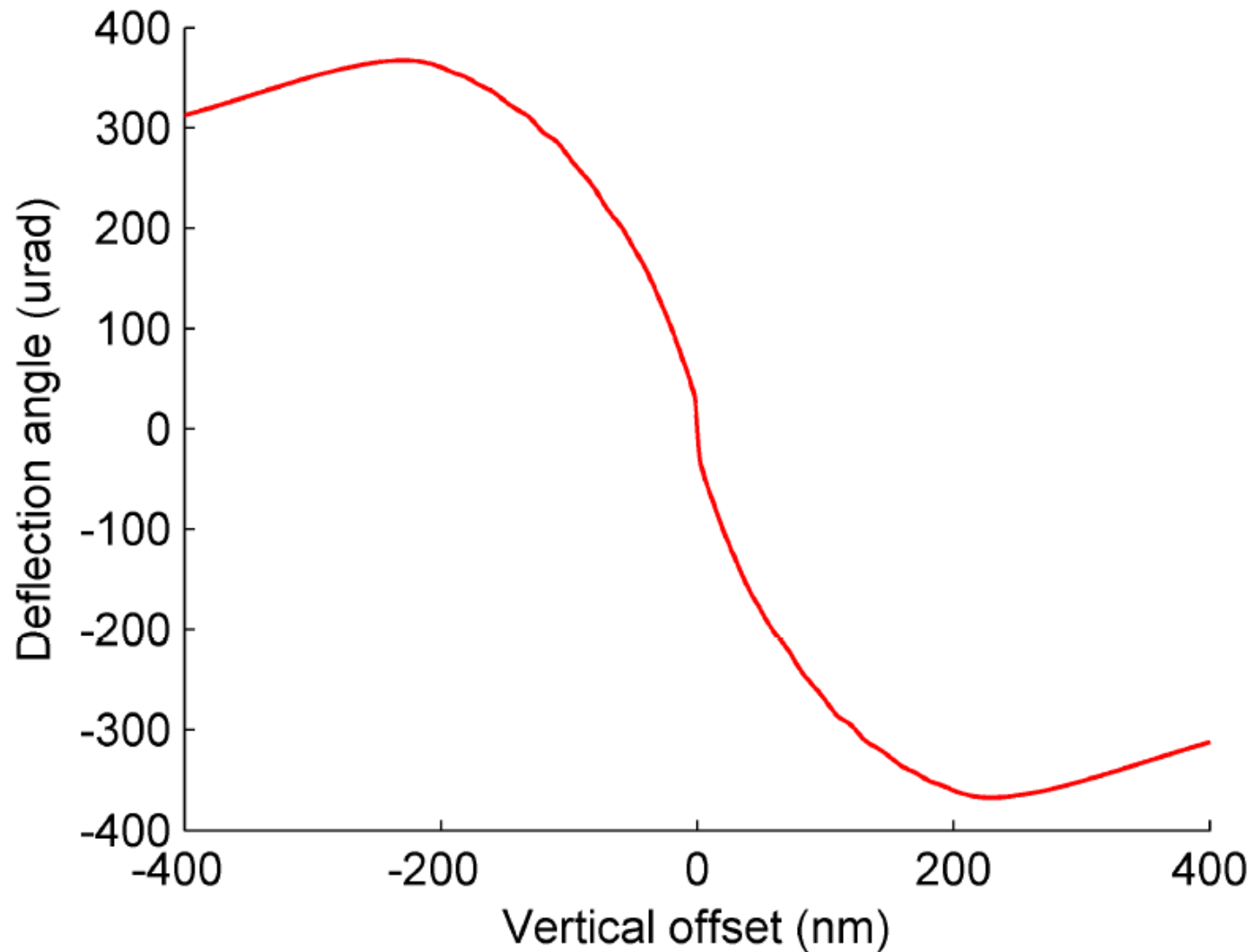
IP intra-train beam feedback concept

Last line of defence against relative beam misalignment

**Measure vertical position of outgoing beam and hence beam-beam kick angle**

Use fast amplifier and kicker to correct vertical position of beam incoming to IR

Kicker

Amp

Delay

Processor

+

BPM
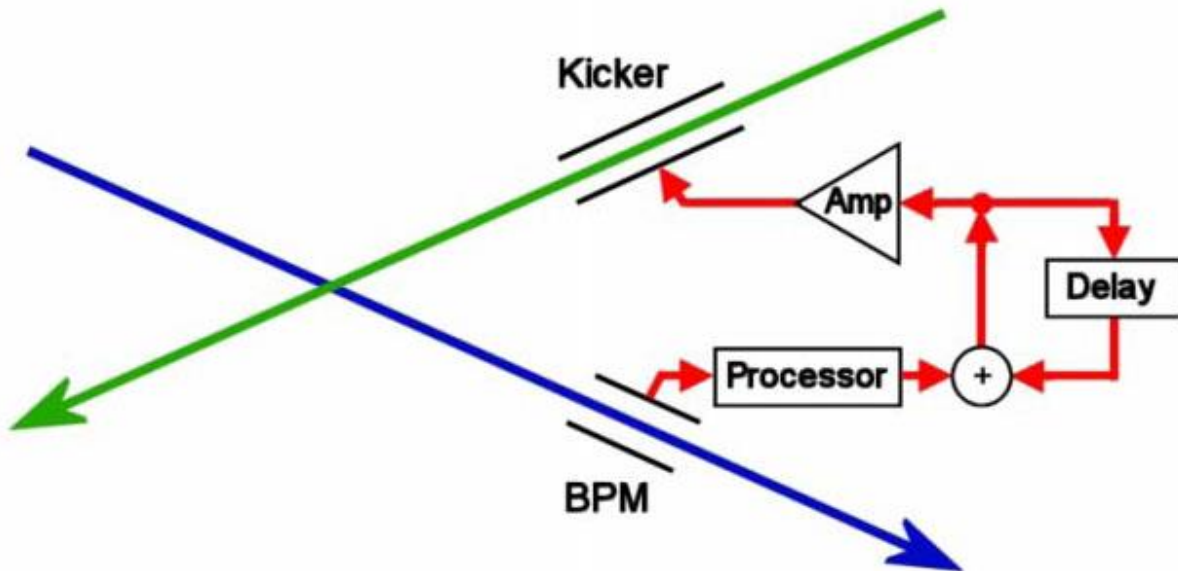
FONT – Feedback On Nanosecond Timescales:

Robert Apsimon, Neven Blaskovic Kraljevic, Douglas Bett, Ryan Bodenstein, Talitha Bromwich, Philip Burrows, Glenn Christian, Christine Clarke, Ben Constance, Michael Davis, Tony Hartin, Young Im Kim, Simon Jolly, Steve Molloy, Gavin Neson, Colin Perry, Rebecca Ramjiawan, Javier Resta Lopez, Jack Roberts, Christina Swinson

Luminosity vs. deflection (ILC500)
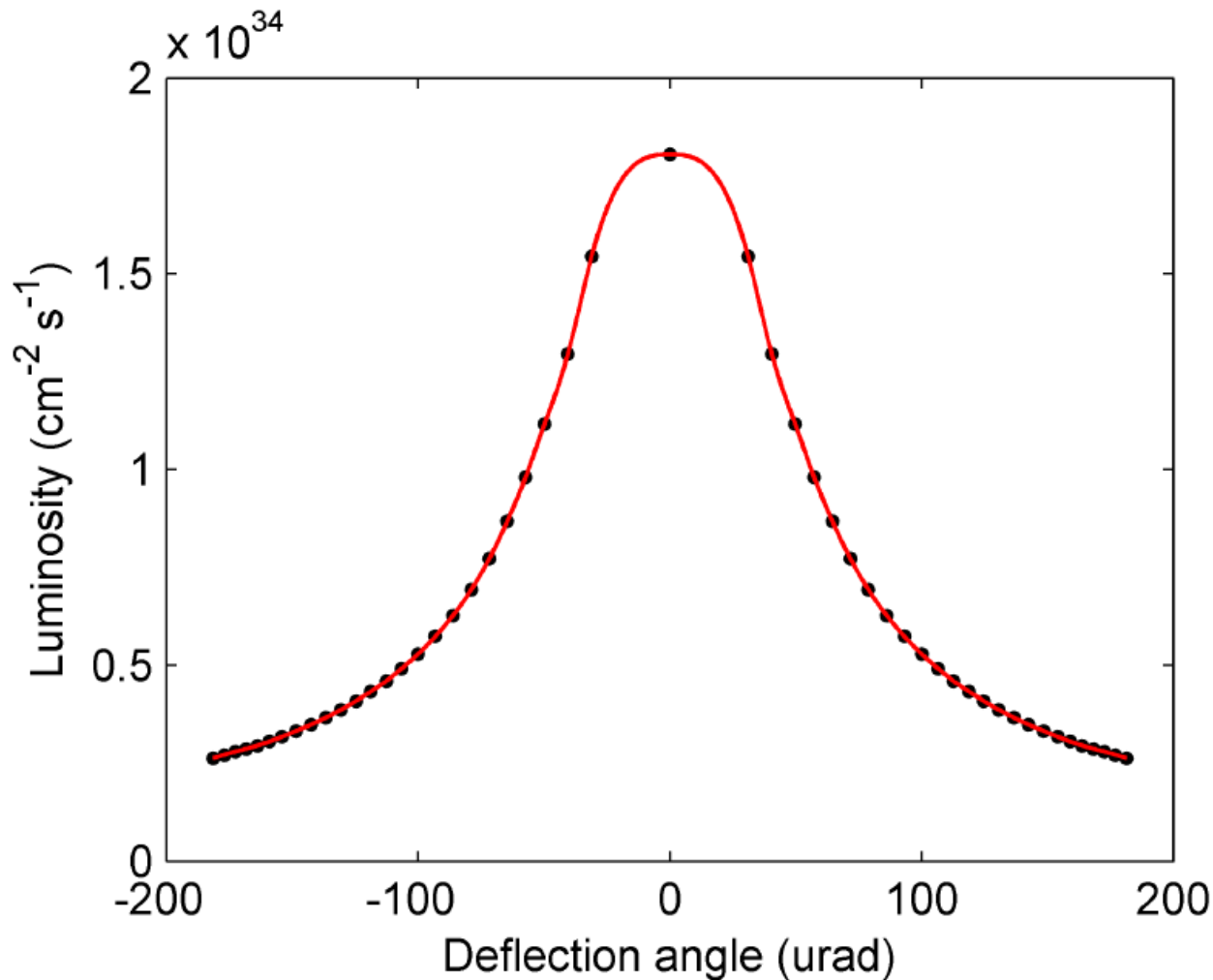
At peak:

1% lumi loss

= 13 urad angle

= 50 um offset
  at FB BPM

General considerations

Time structure of bunch train:

    ILC: c. 1300 bunches w. c. 500 ns separation

    CLIC: c. 300   bunches w. c. 0.5 ns separation

Feedback latency:

    ILC: O(100ns) latency budget allows **digital** approach

    CLIC: O(10ns)   latency requires **analogue** approach

Recall speed of light: c = 30 cm / ns:

    every metre of spatial separation costs c. 7ns (round-trip)!

    FB hardware should be close to IP (especially for CLIC!)

Two systems, one on each side of IP, allow for redundancy

IP FB Design Status: ILC

Engineering design documented in ILC TDR (2013):

1. IP beam position feedback:

    beam position correction up to +- 300 nm vertical at IP

2. IP beam angle feedback: hardware located few 100 metres upstream

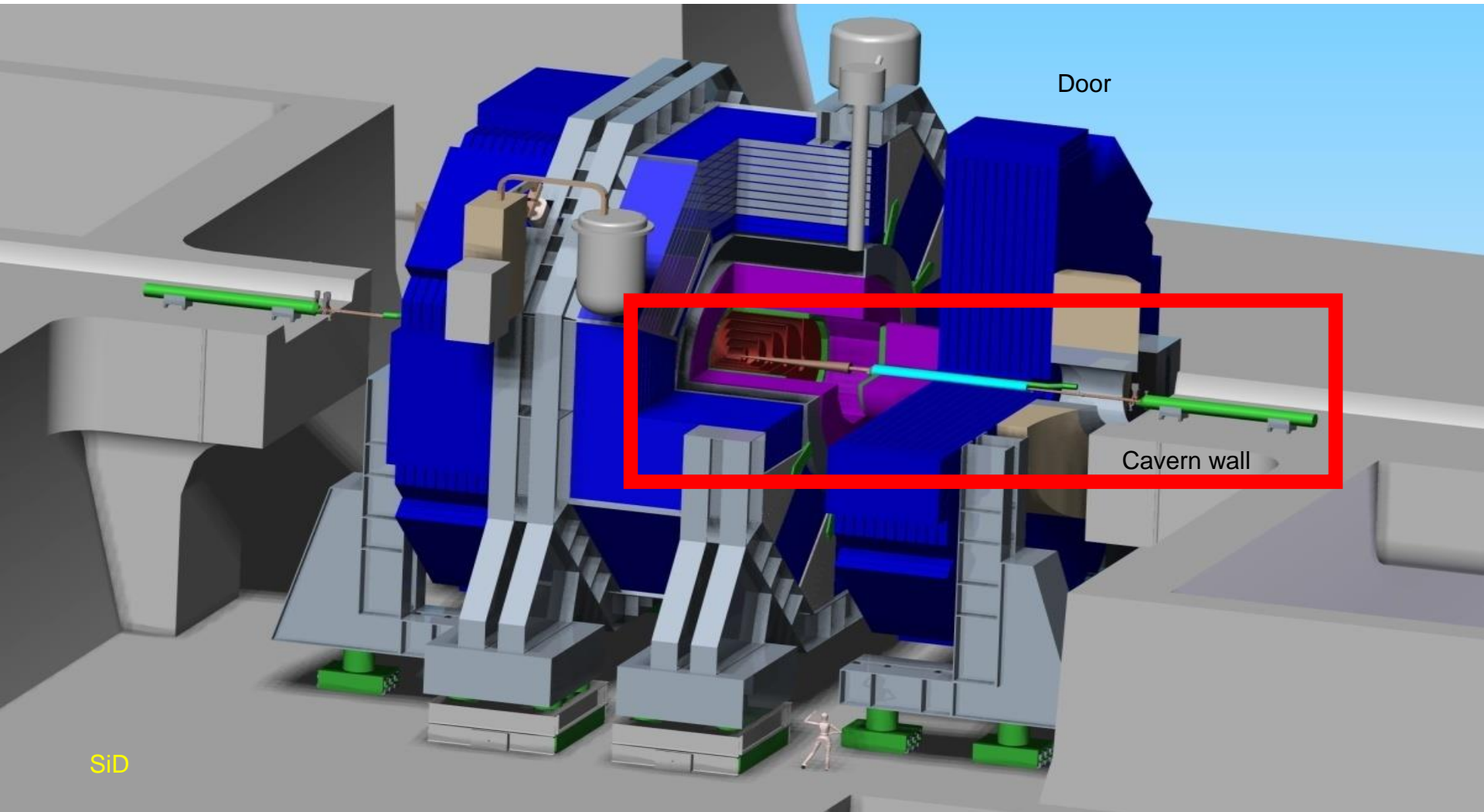   **conceptually very similar to position FB, less critical**

3. Bunch-by-bunch luminosity signal (from 'BEAMCAL')

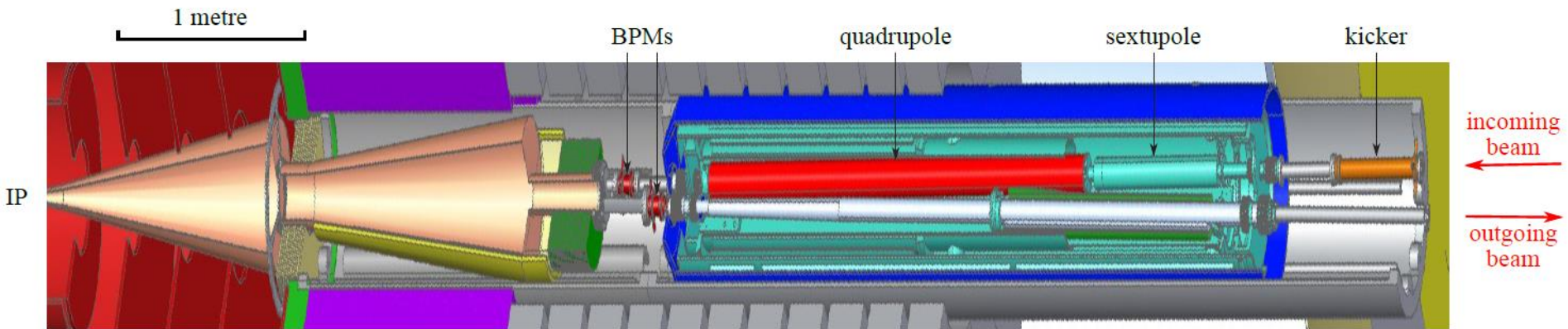   **'special' systems requiring dedicated hardware + data links**
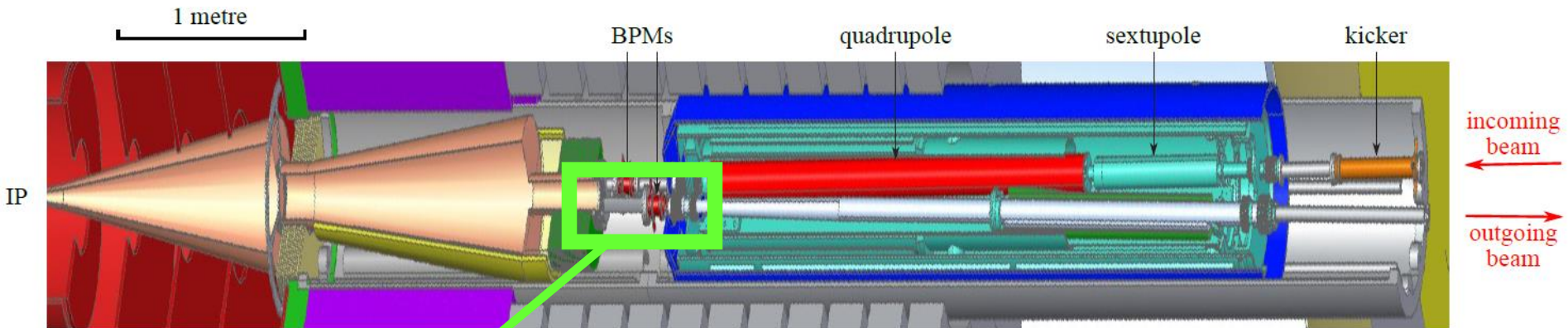
ILC Interaction Region (SiD)

Door

Cavern wall

SiD

ILC Interaction Region (SiD)

Door

Cavern wall

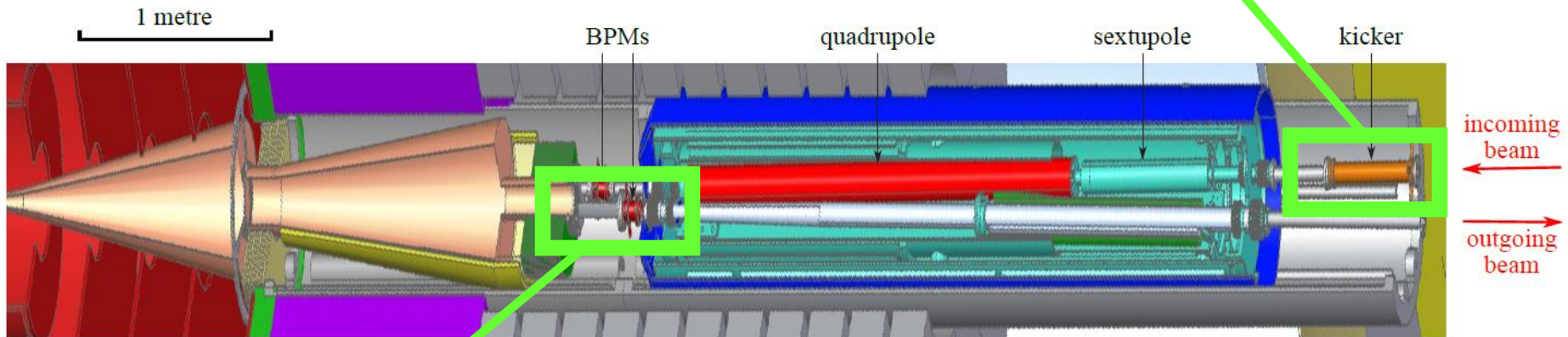SiD
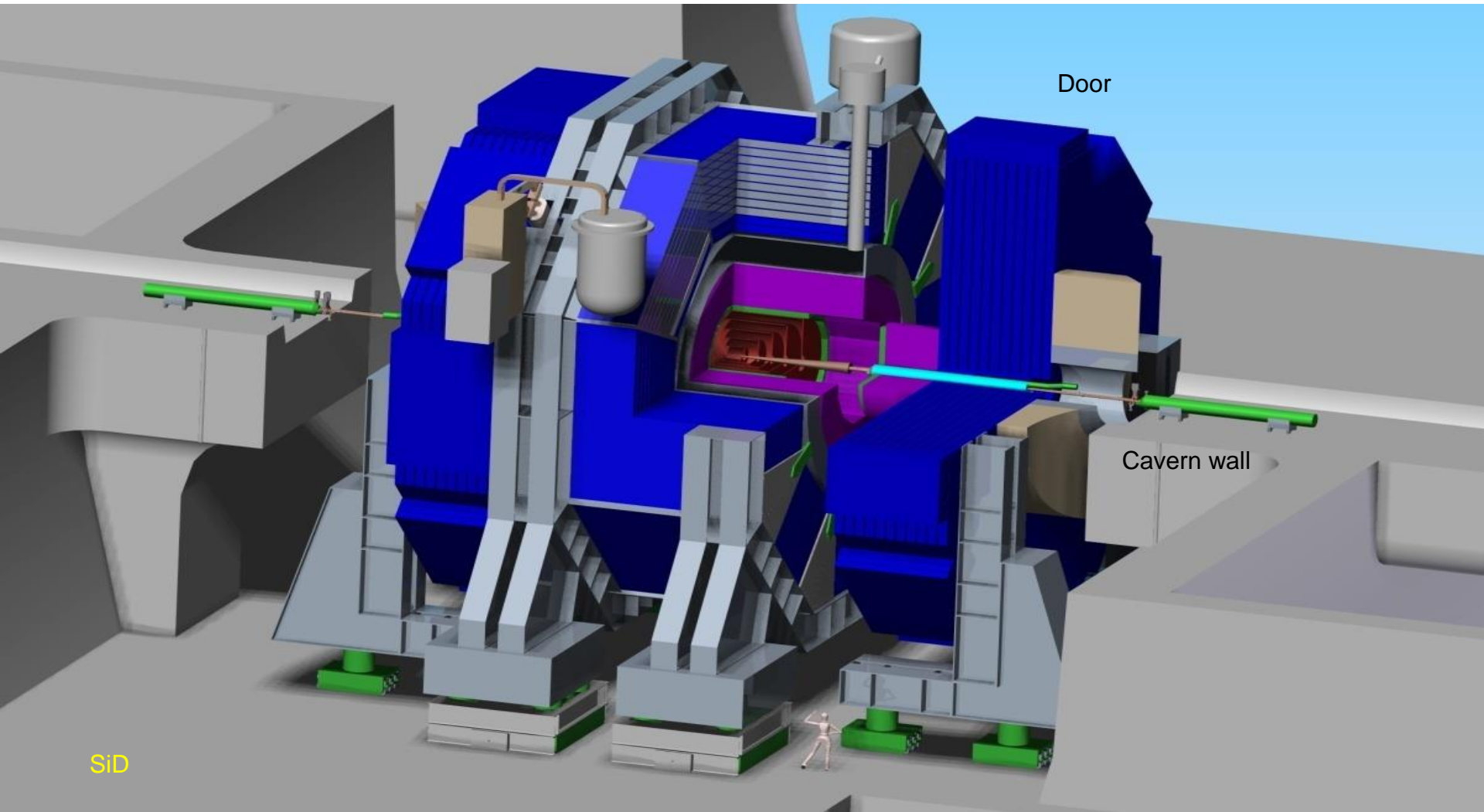
Final-focus region (SiD)

Final-focus region (SiD)
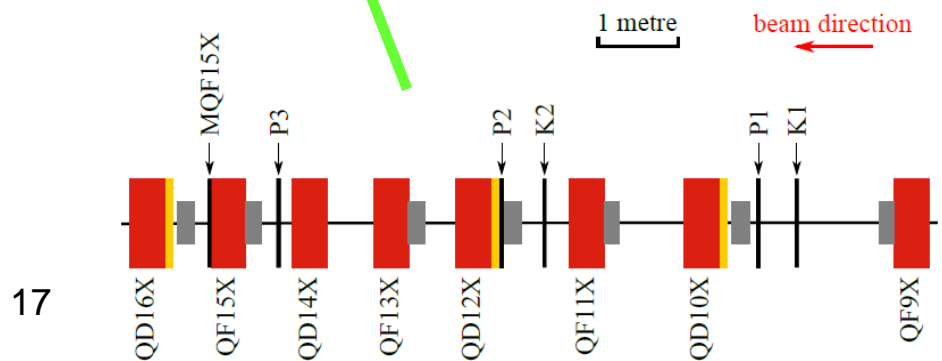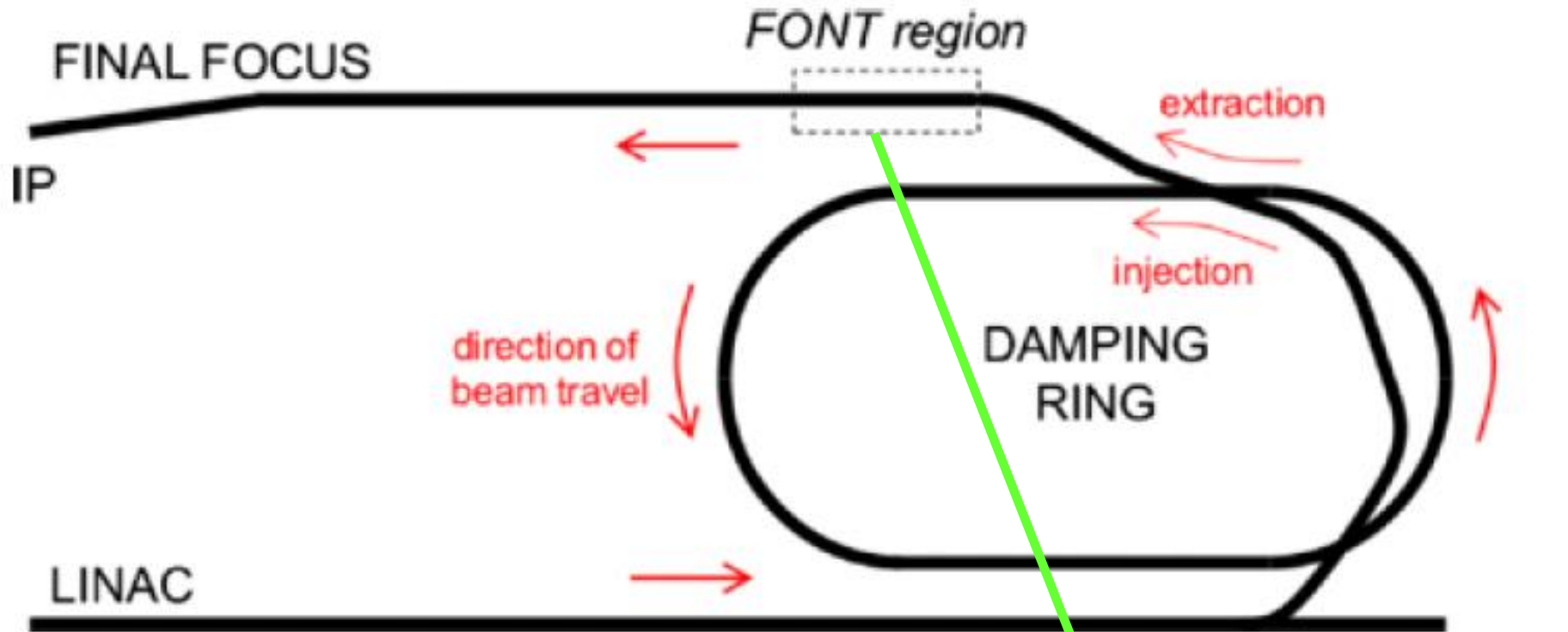

FB BPM on outgoing beamline

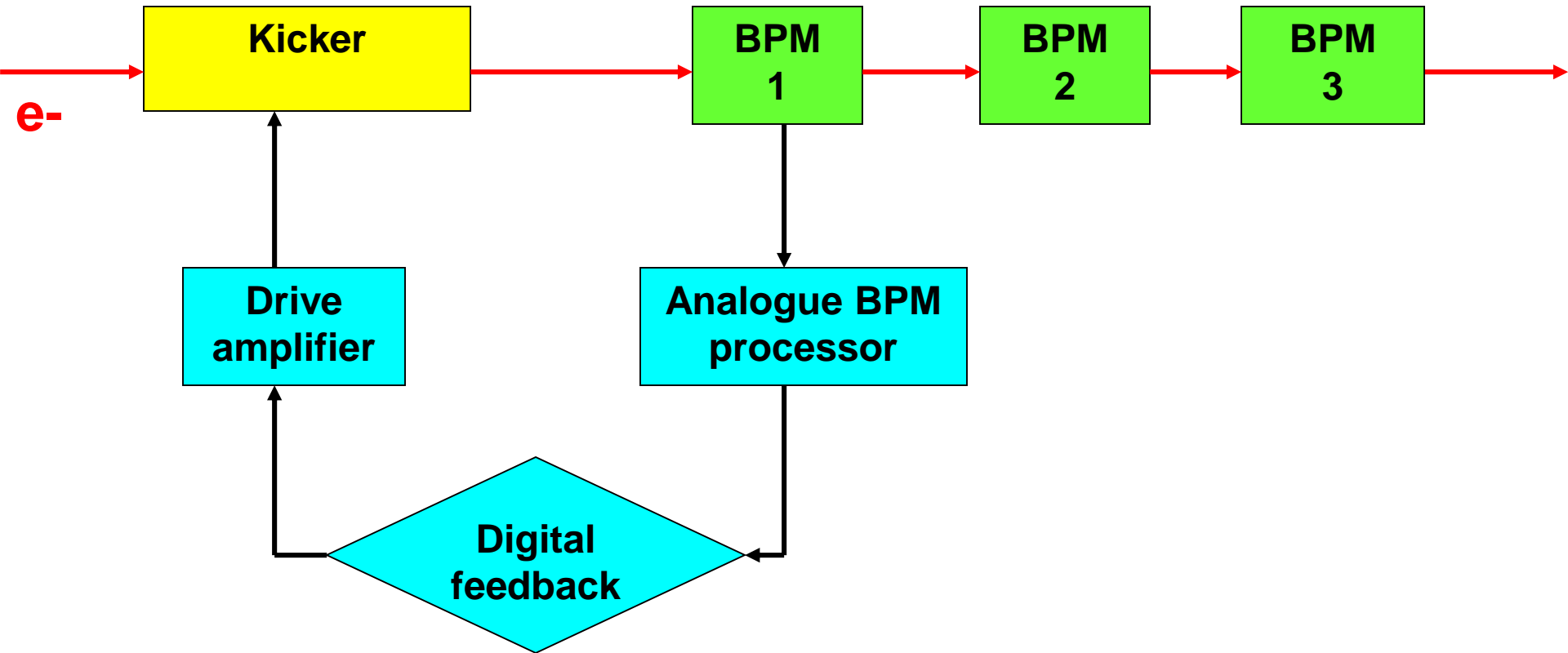# Final-focus region (SiD)

FB kicker on incoming beamline

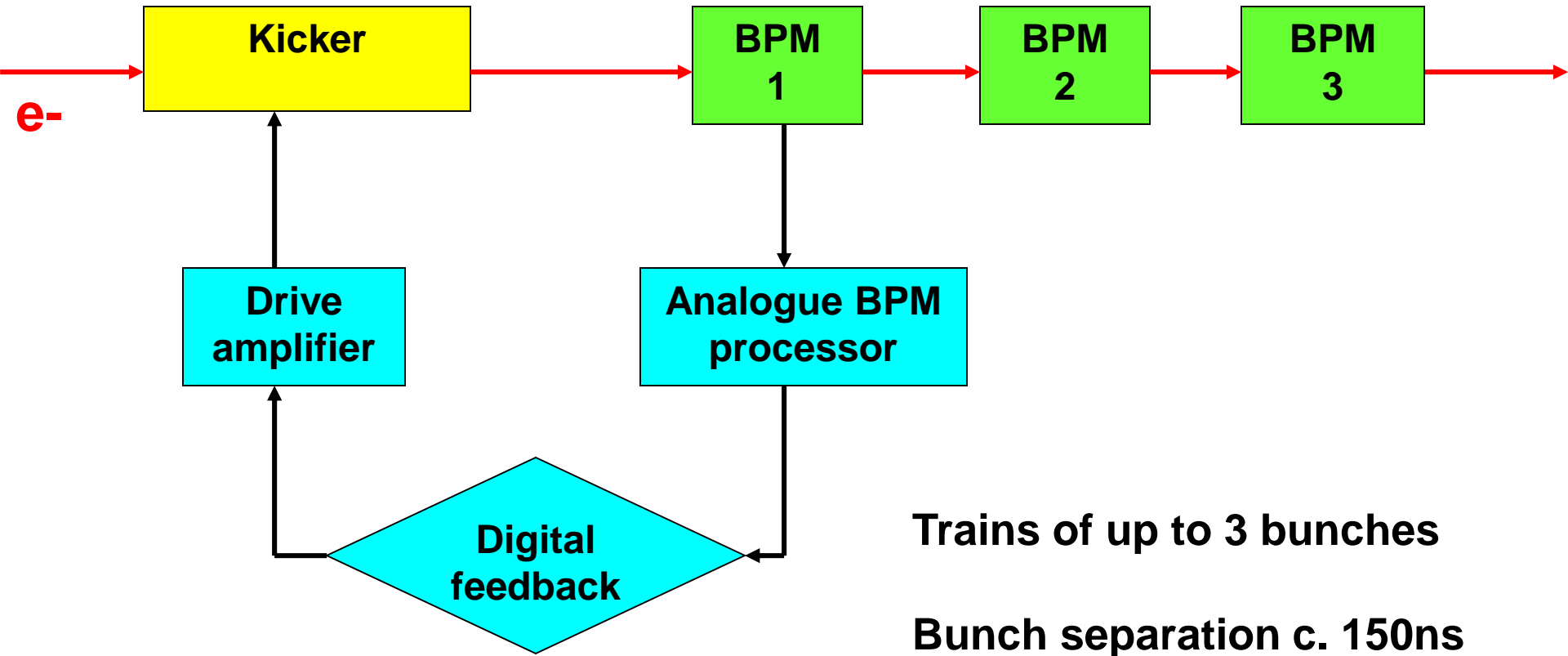BPM on outgoing beamline

KEK Accelerator Test Facility (ATF2)

17

ILC FB prototype: FONT at KEK/ATF

ILC FB prototype: FONT at KEK/ATF

e-

Kicker → BPM 1 → BPM 2 → BPM 3

Drive amplifier

Analogue BPM processor

Digital feedback

Trains of up to 3 bunches

Bunch separation c. 150ns

ILC prototype: FONT4 at KEK/ATF

e-

BPM 2

BPM 3

TRACO POWER

ILC prototype: FONT4 at KEK/ATF

e-

BPM 2

BPM 3

BPM resolution   **~ 0.3um**
Latency   **~ 150ns**
Drive power   **> 300nm**
                   @ ILC
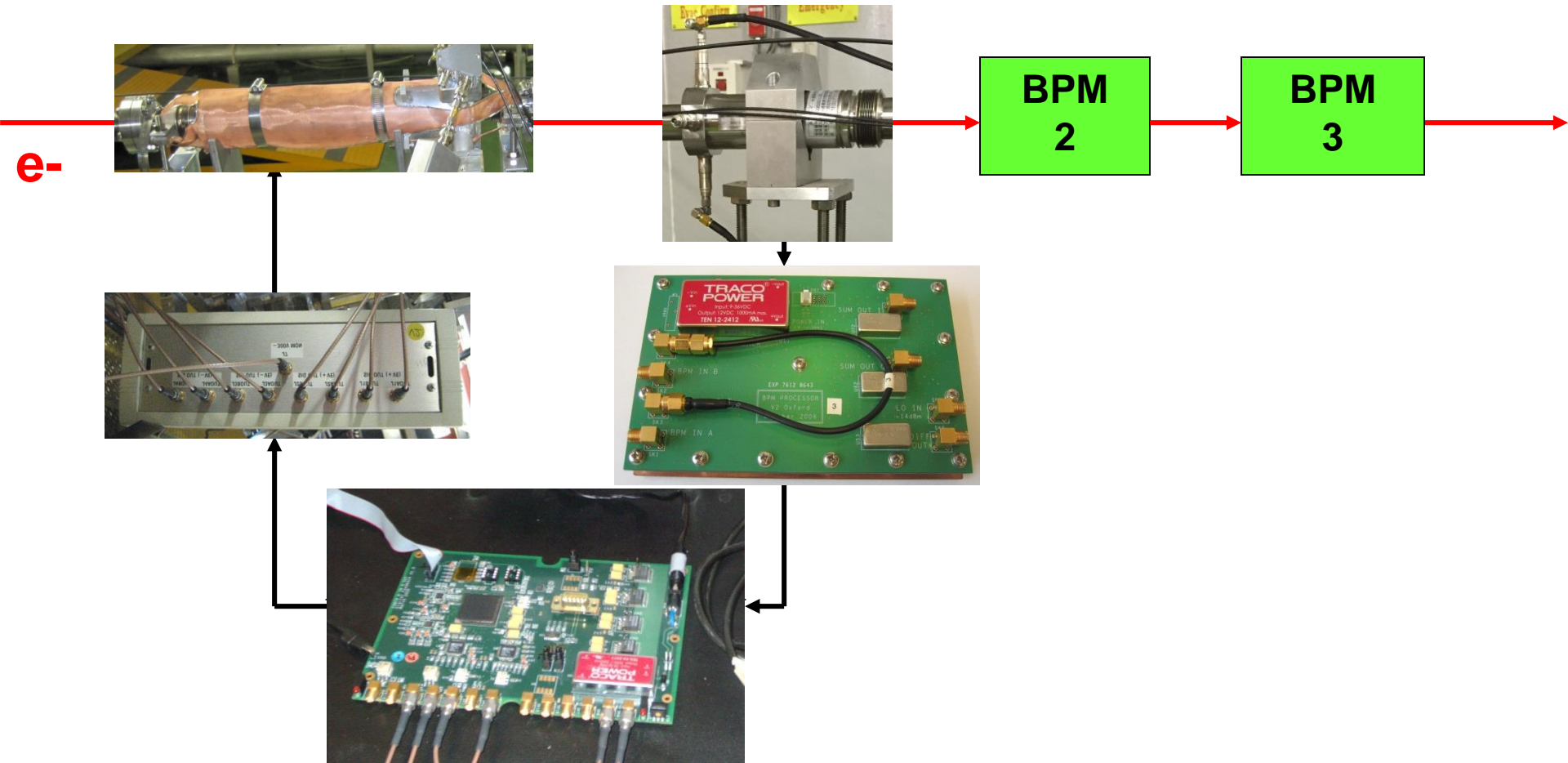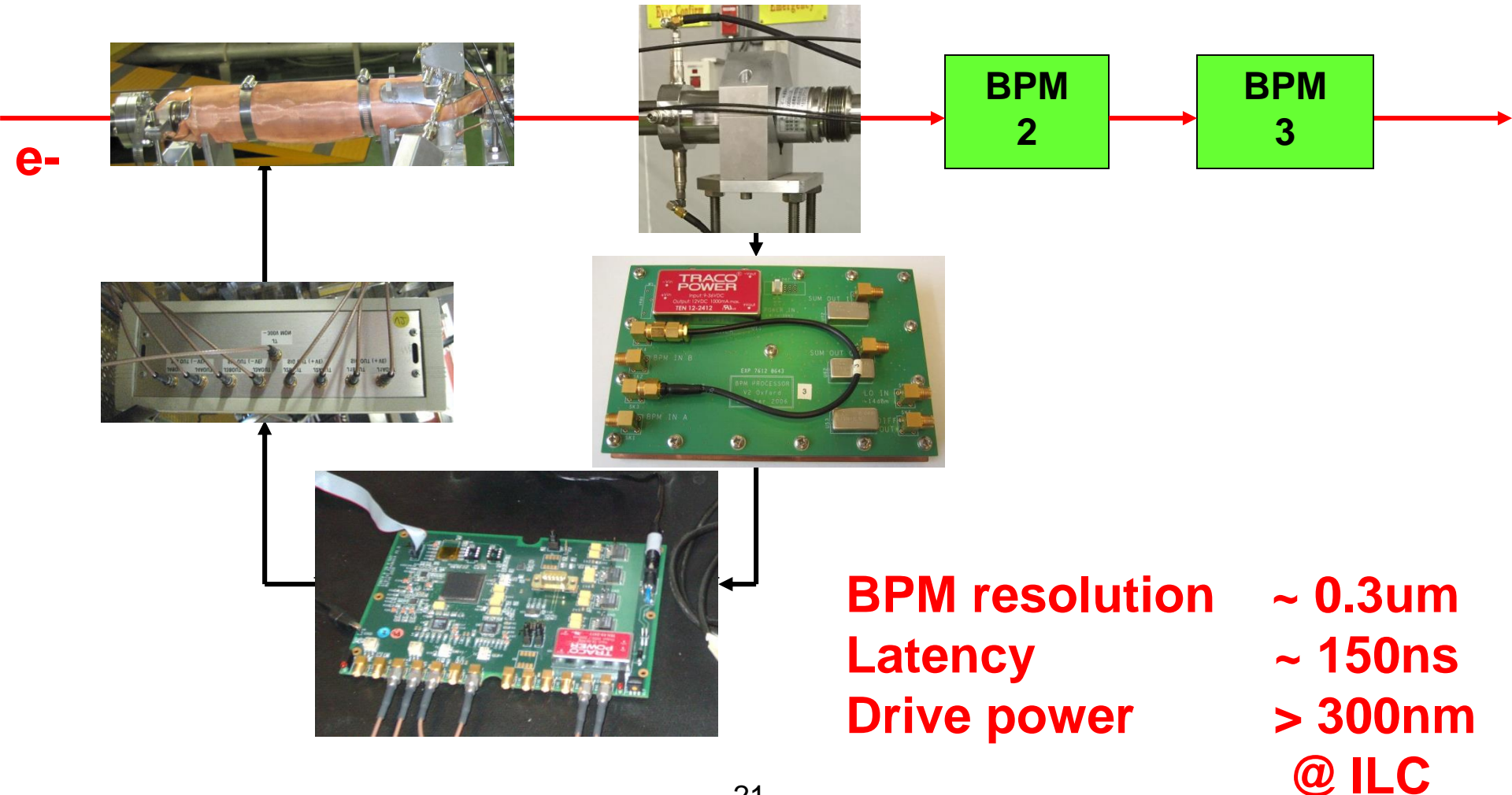
FONT digital feedback board
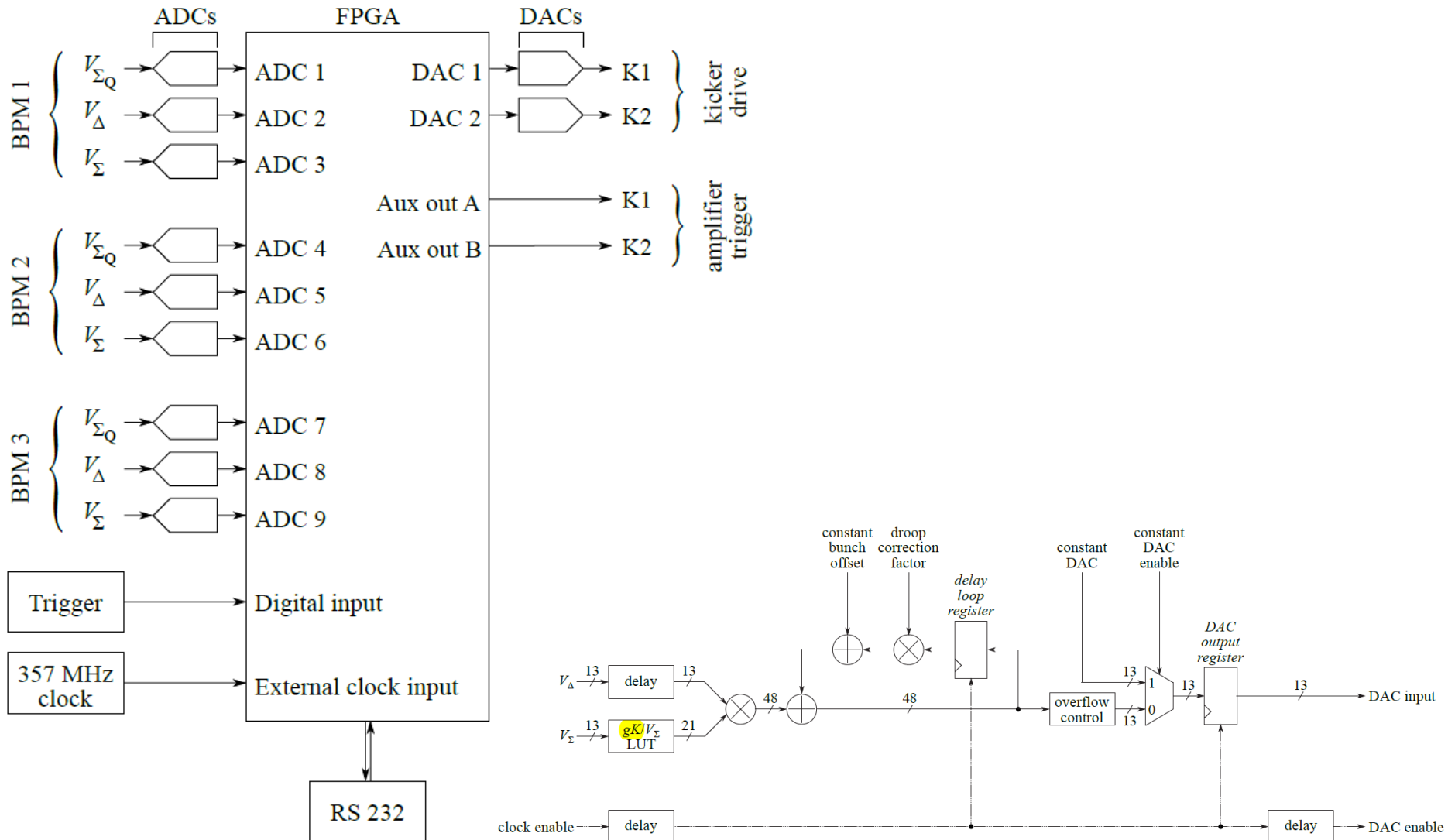
FONT4 performance

FONT4 performance

FIG. 19. Distributions of positions with feedback off (blue) and feedback on (red) for bunch 2 at P3 with incoming, uncorrected position jitters of (a) ~2 μm, (b) ~22 μm, and (c) ~45 μm.

FONT ILC prototype performance
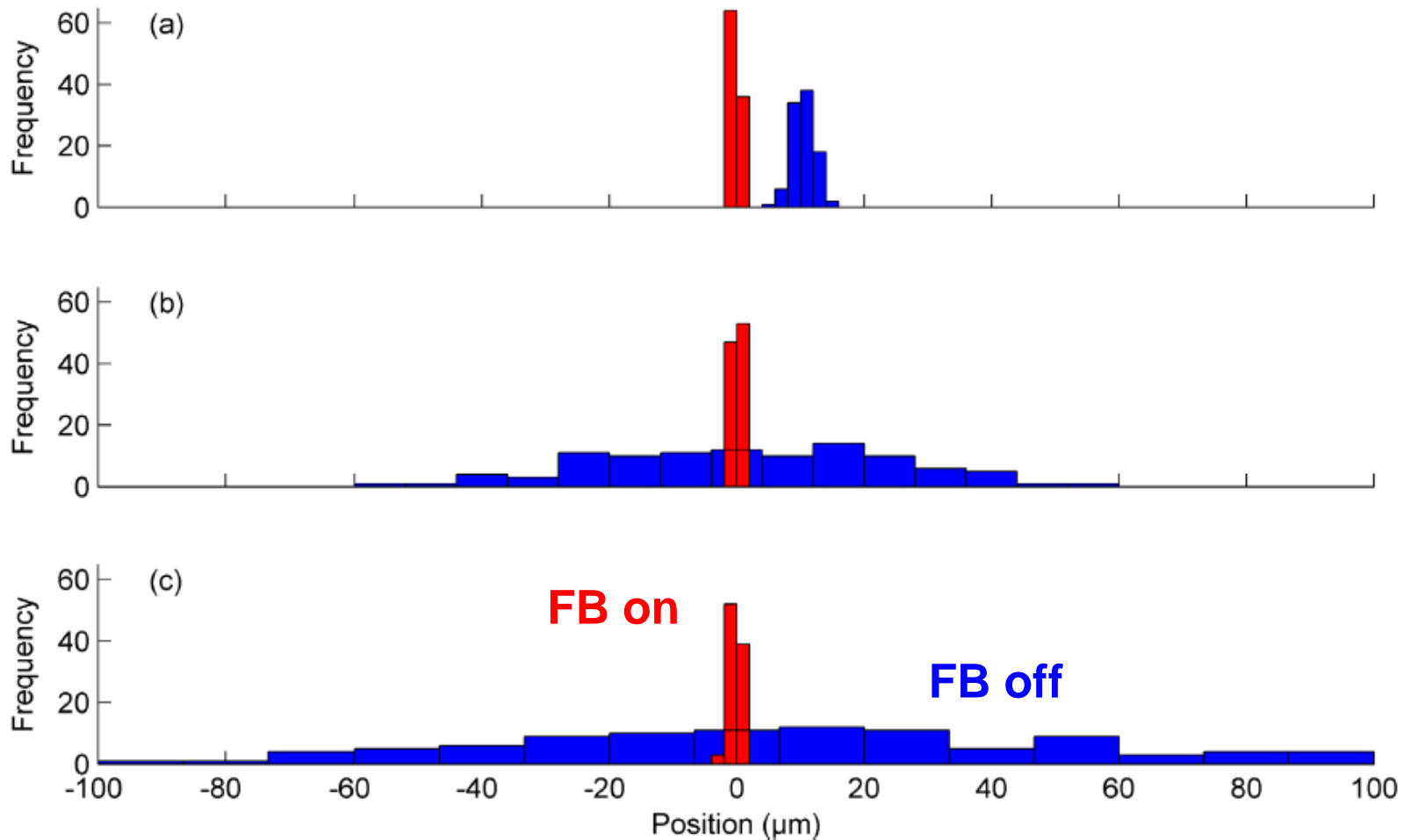
TABLE IV. Comparison of the IP feedback performance required at the ILC with that achieved by the FONT feedback system at ATF.

		ILC	ATF
Energy per beam	GeV	250	1.3
IP feedback latency	ns	554	148
BPM dynamic range	μm	±1400	±1500
BPM resolution	μm	~ 50	~ 1
Beam angle correction range	nrad	$\sim \pm60$	$\sim \pm180^{\dagger}$

$\dagger$ scaled by the ATF/ILC beam energy ratio

FB BPM paper

Design and performance of a high resolution, low latency stripline beam position monitor system

R. J. Apsimon,[*] D. R. Bett,[†] N. Blaskovic Kraljevic, P. N. Burrows, G. B. Christian,[‡]
C. I. Clarke,[§] B. D. Constance, H. Dabiri Khah, M. R. Davis, C. Perry,
J. Resta López,[‖] and C. J. Swinson[¶]

*John Adams Institute for Accelerator Science at University of Oxford, Denys Wilkinson Building,
Keble Road, Oxford OX1 3RH, United Kingdom*
(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 ± 0.1 ns. A single-pass beam position resolution of 291 ± 10 nm has been achieved, using a beam with a bunch charge of approximately 1 nC.

ILC IP FB prototype paper

Design and operation of a prototype interaction point beam collision feedback system for the International Linear Collider

R. J. Apsimon,[*] D. R. Bett, N. Blaskovic Kraljevic,[†] R. M. Bodenstein, T. Bromwich,
P. N. Burrows, G. B. Christian,[‡] B. D. Constance, M. R. Davis, C. Perry, and R. Ramjiawan

John Adams Institute for Accelerator Science at University of Oxford,
Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom

A high-resolution, intratrain position feedback system has been developed to achieve and maintain collisions at the proposed future electron-positron International Linear Collider (ILC). A prototype has been commissioned and tested with a beam in the extraction line of the Accelerator Test Facility at the High Energy Accelerator Research Organization in Japan. It consists of a stripline beam position monitor (BPM) with analogue signal-processing electronics, a custom digital board to perform the feedback calculation, and a stripline kicker driven by a high-current amplifier. The closed-loop feedback latency is 148 ns. For a three-bunch train with 154 ns bunch spacing, the feedback system has been used to stabilize the third bunch to 450 nm. The kicker response is linear, and the feedback performance is maintained, over a correction range of over ± 60 μm. The propagation of the correction has been confirmed by using an independent stripline BPM located downstream of the feedback system. The system has been demonstrated to meet the BPM resolution, beam kick, and latency requirements for the ILC.

Simulated ILC IP FB performance
(500 GeV)
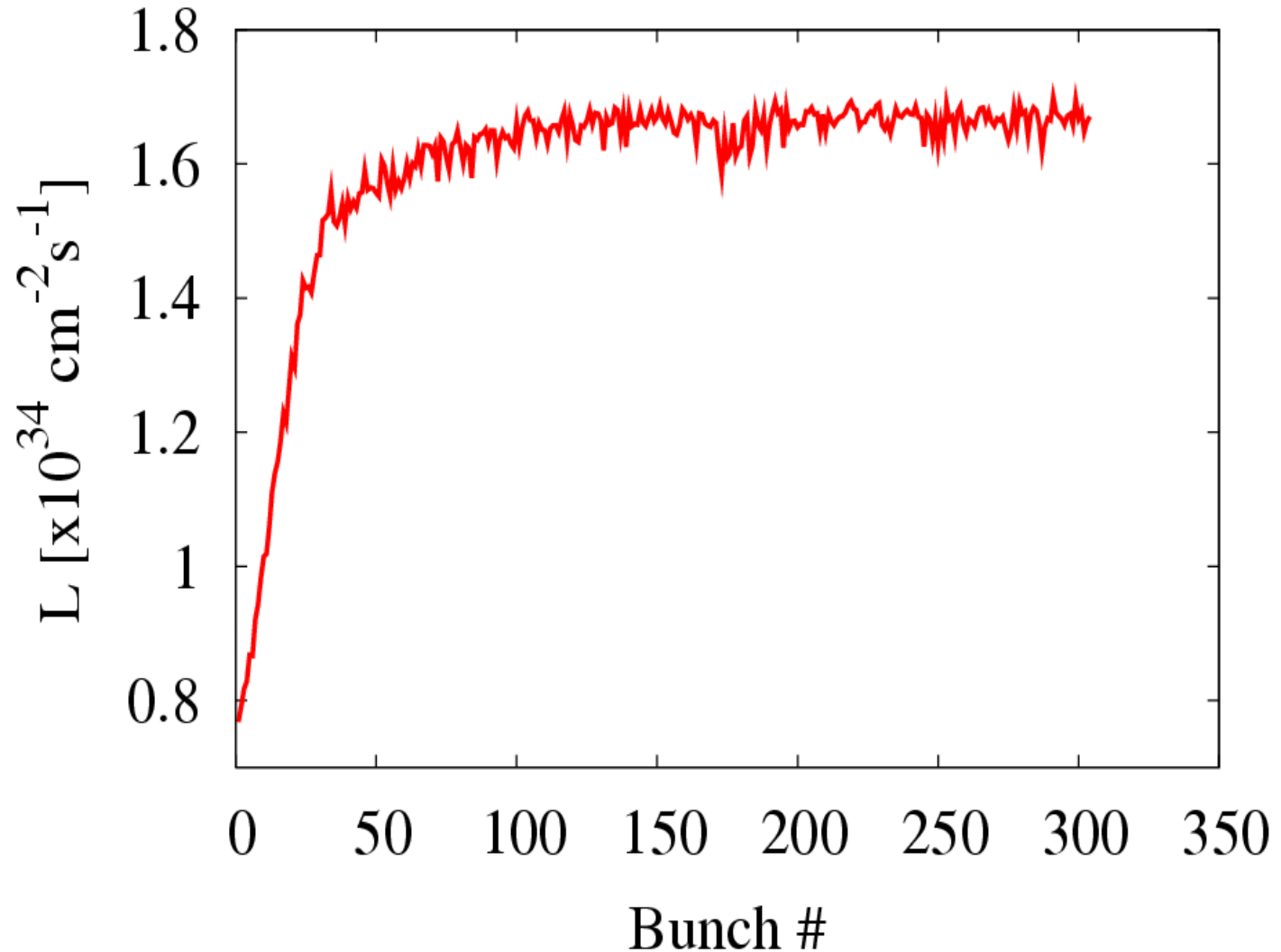
IP FB Design Status: CLIC

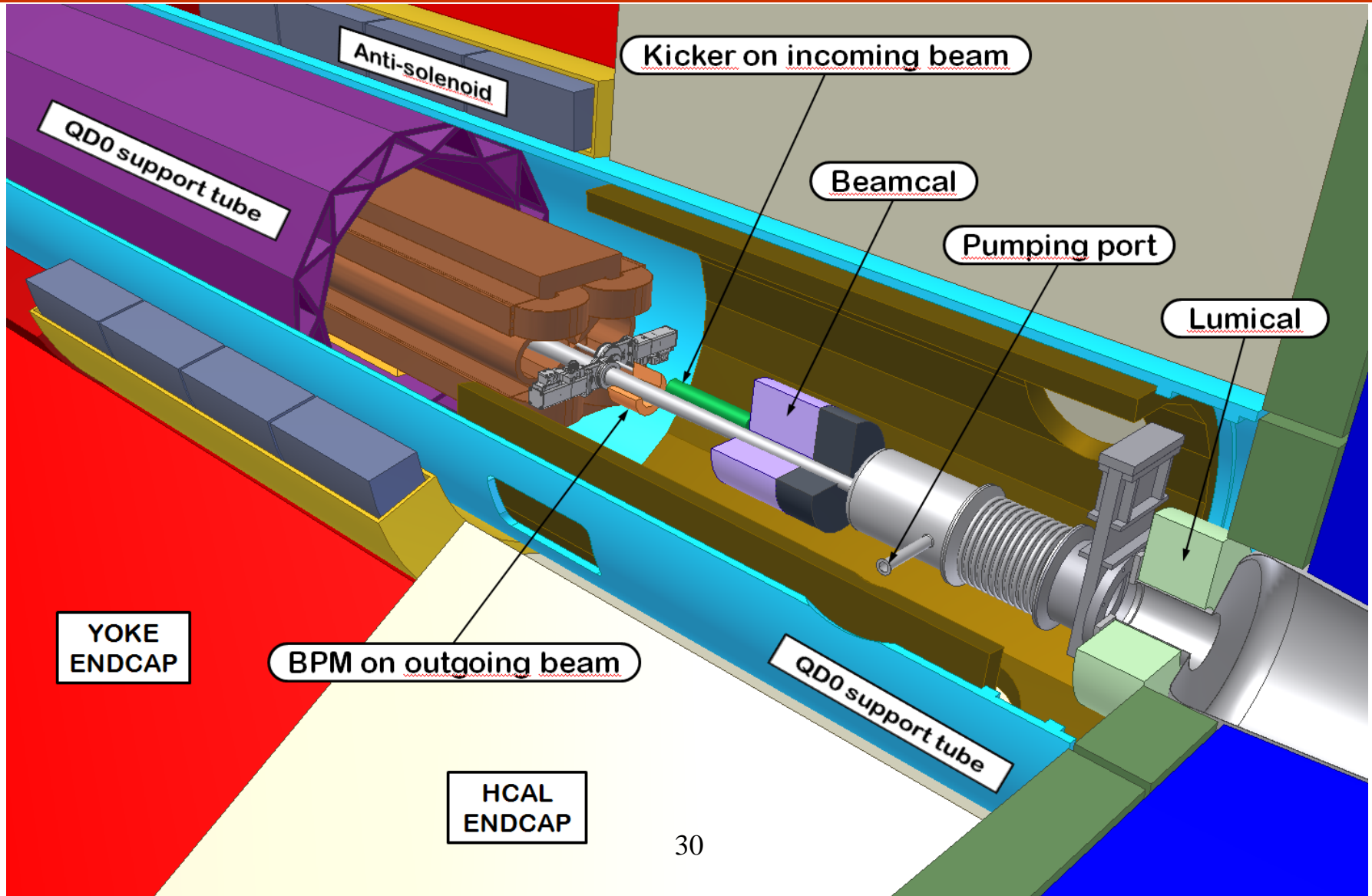**Conceptual design developed and documented in CLIC CDR (2012)**

NB primary method for control of beam collision overlap is via vibration isolation of the FF magnets, and dynamic correction of residual component motions
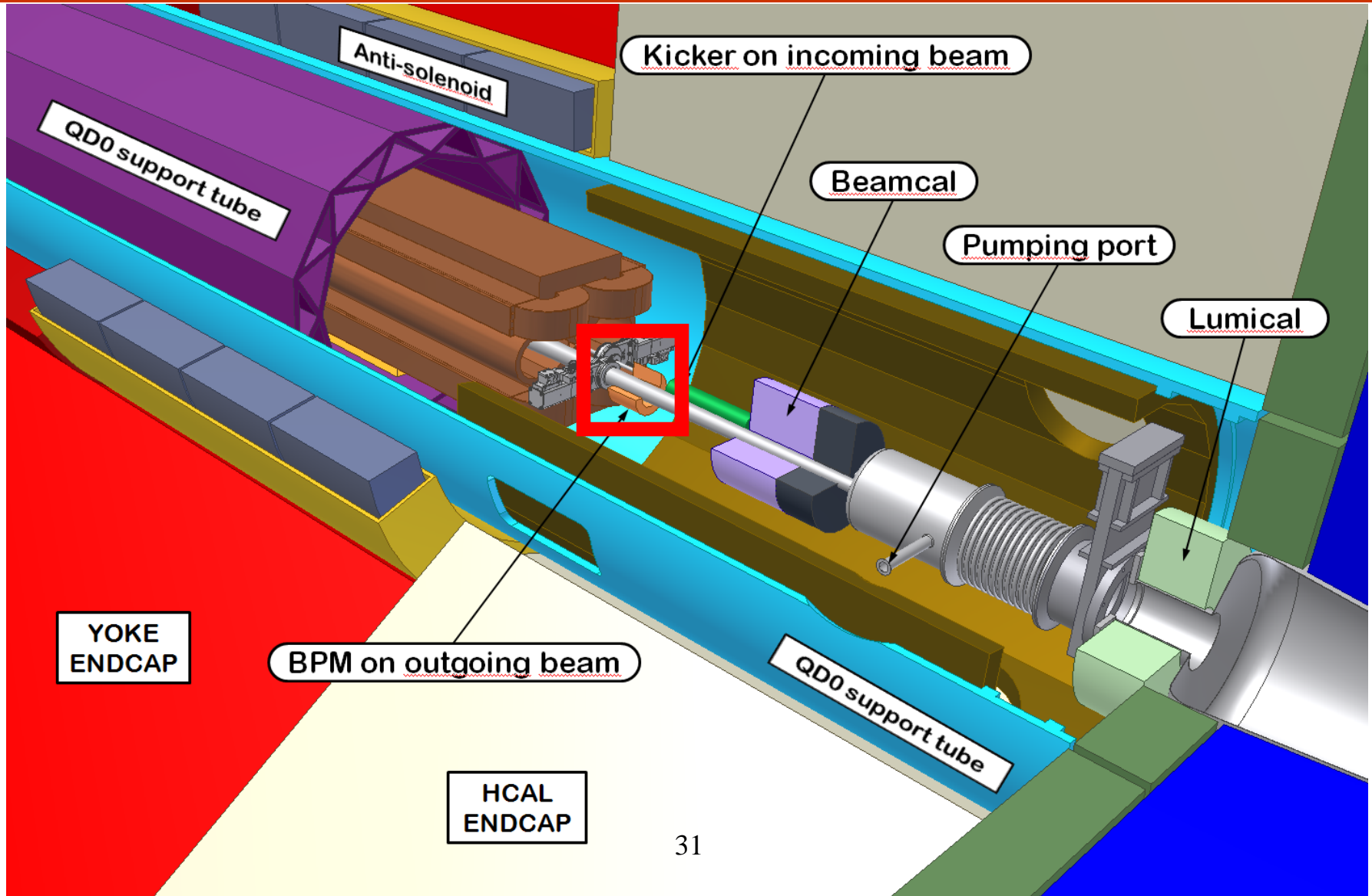
IP position feedback:

    beam position correction up to +- 50 nm vertical at IP
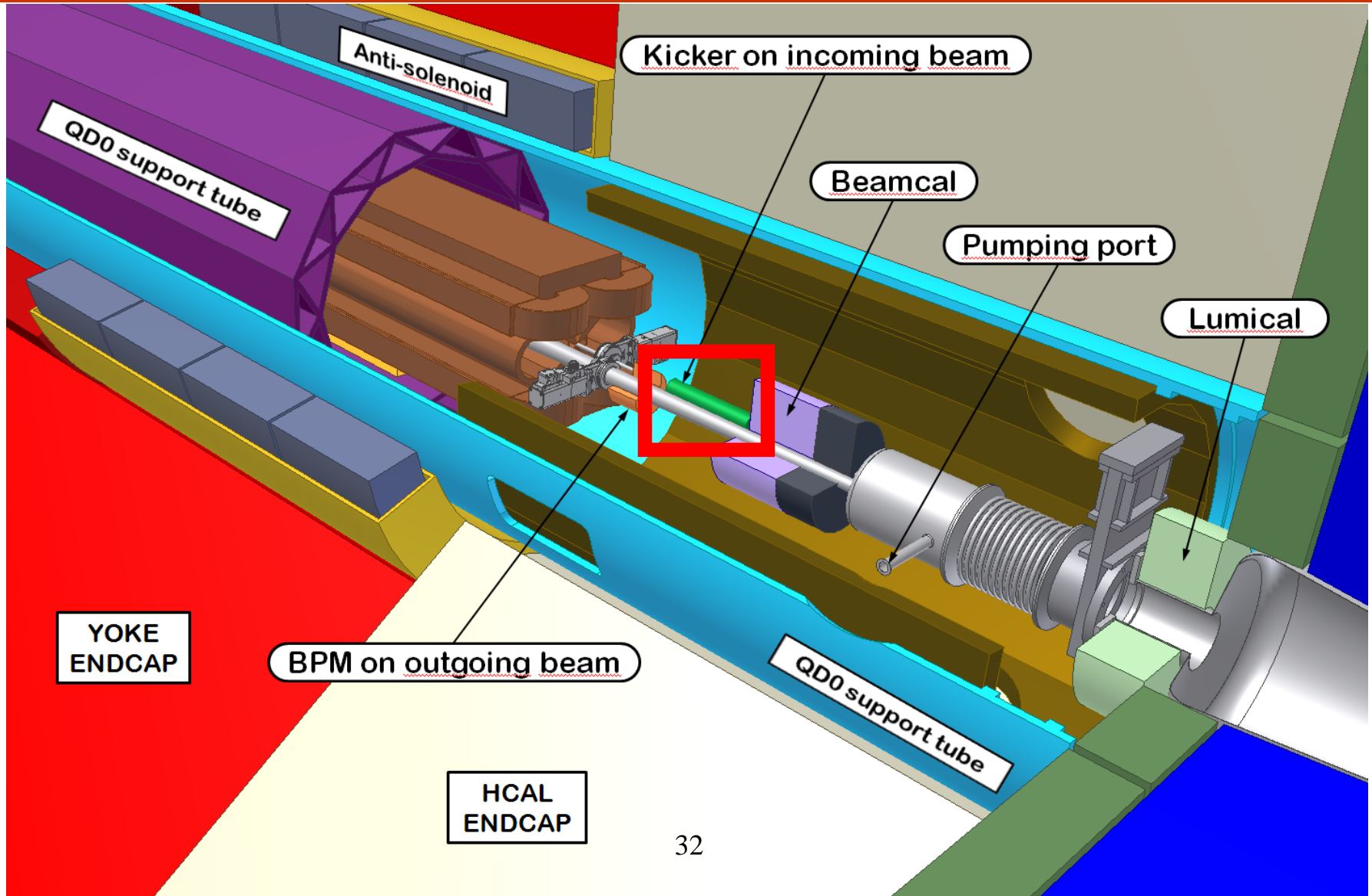
Needs more realistic engineering design
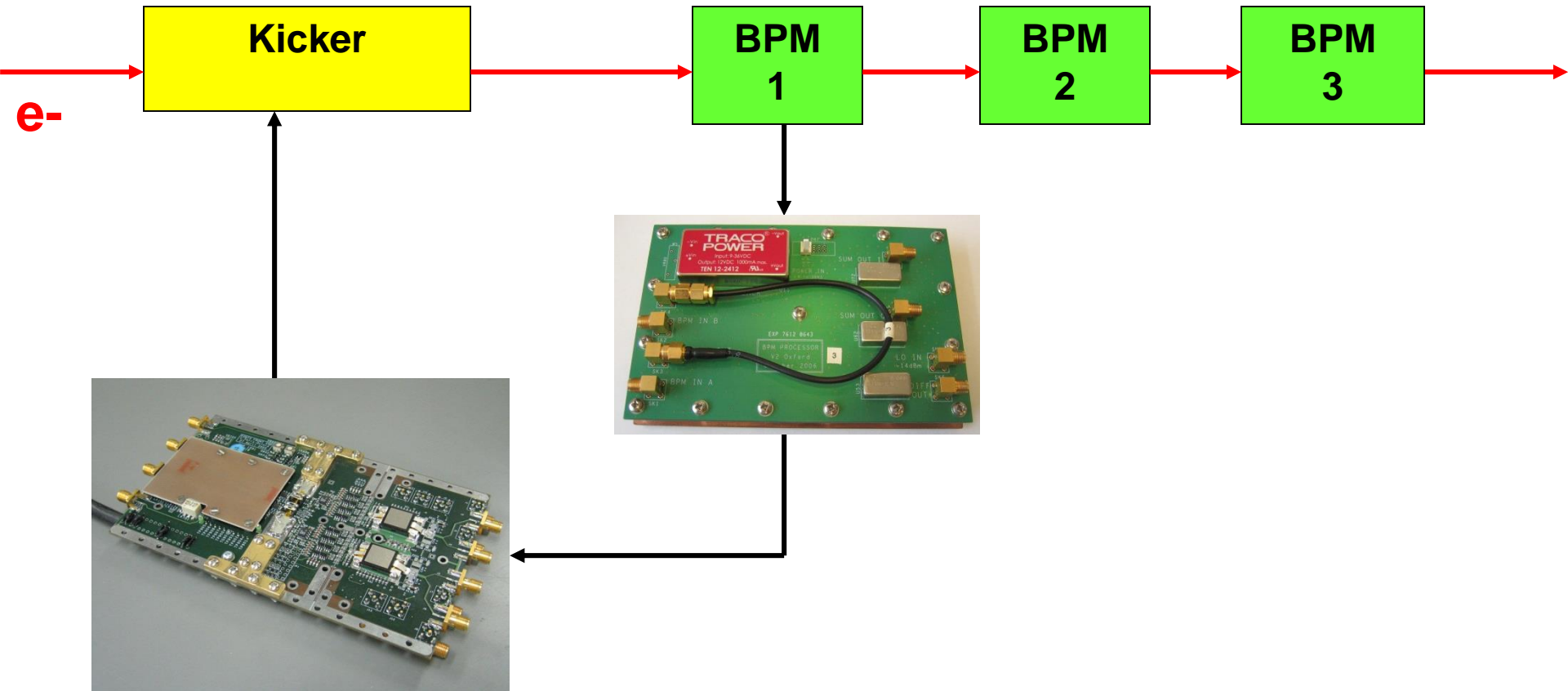
CLIC Final Doublet Region

Anti-solenoid

Kicker on incoming beam

QD0 support tube

Beamcal

Pumping port

Lumical

YOKE ENDCAP

BPM on outgoing beam

QD0 support tube

HCAL ENDCAP

30

CLIC Final Doublet Region

Anti-solenoid

Kicker on incoming beam

QD0 support tube

Beamcal

Pumping port

Lumical

YOKE ENDCAP

BPM on outgoing beam

QD0 support tube

HCAL ENDCAP

31

CLIC Final Doublet Region

CLIC prototype: FONT3 at KEK/ATF

CLIC prototype: FONT3 at KEK/ATF

e- → **Kicker** → **BPM 1** → **BPM 2** → **BPM 3** →
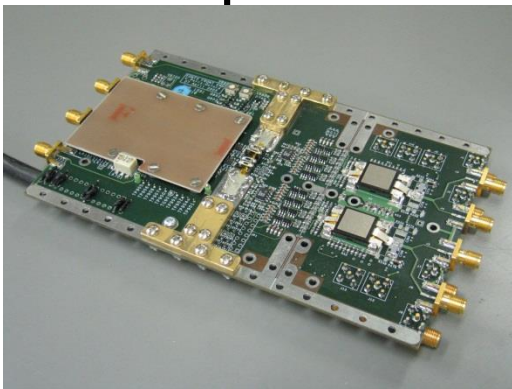
Electronics latency ~ 13ns
Drive power   > 50nm
**   @ CLIC**

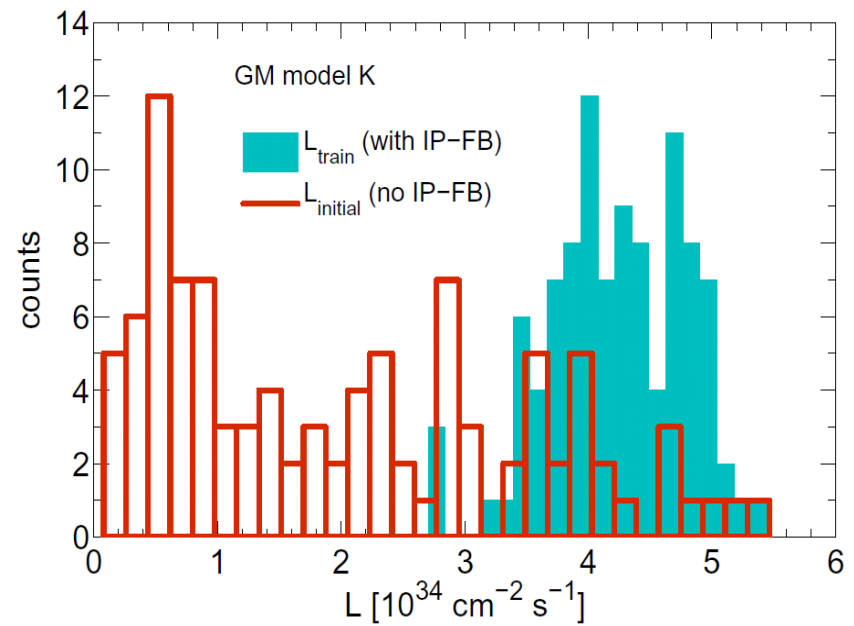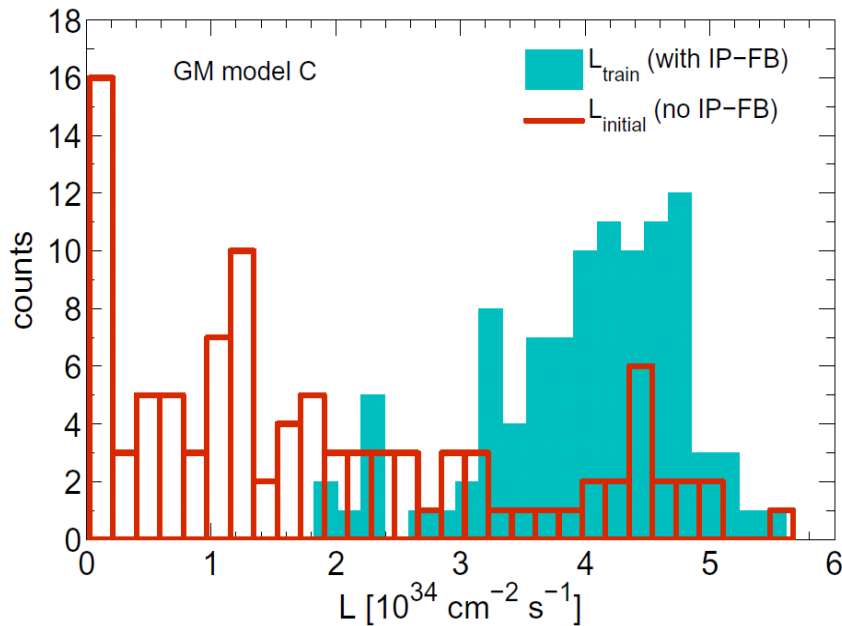# CLIC IP FB performance (CDR)

Single random seed of GM C
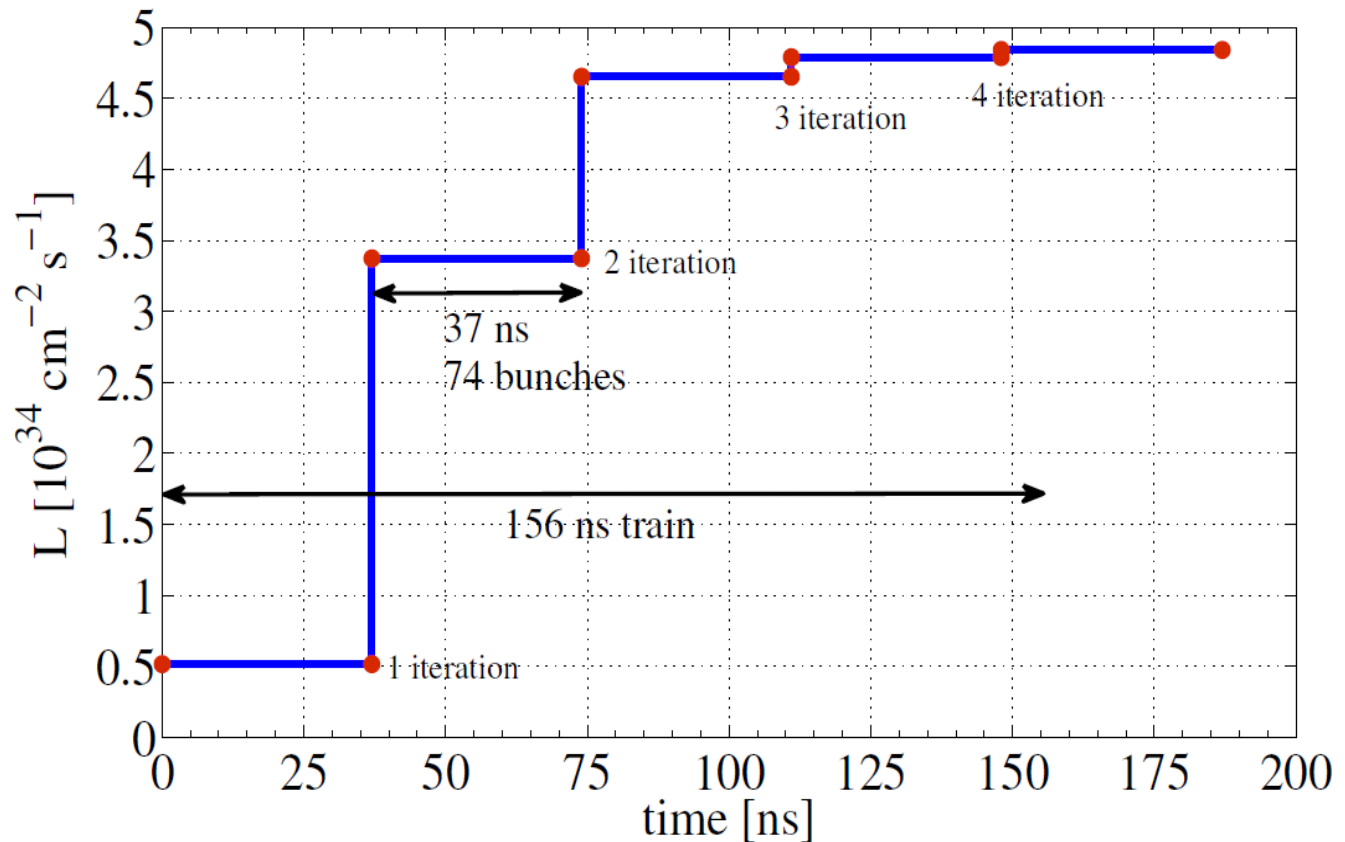
CLIC IP FB luminosity performance

For noisy sites:

→ **factor 2 - 3 improvement**

CLIC IP FB simulation paper

Luminosity performance studies of the compact linear collider with intra-train feedback system at the interaction point

J. Resta-López,[1] P.N. Burrows and G. Christian

John Adams Institute for Accelerator Science, Oxford University,
Oxford, OX1 3RH, U.K.

E-mail: j.restalopez@physics.ox.ac.uk

ABSTRACT: To achieve the design luminosity at future linear colliders, control of beam stability at the sub-nanometre level at the interaction point will be necessary. Any source of beam motion which results in relative vertical offsets of the two beams at the interaction point may significantly reduce the luminosity from the nominal value. Beam-based intra-train feedback systems located in the interaction region are foreseen to correct the relative beam-beam offset and thus to steer the two beams into collision. These feedback systems must be capable of acting within the bunch train. In addition, these feedback systems might considerably help to relax the tight stability tolerances required for the final doublet magnets. For the Compact Linear Collider (CLIC), the extremely short nominal bunch spacing (0.5 ns) and very short nominal pulse duration (156 ns) make the intra-train feedback implementation technically very challenging. In this paper the conceptual design of an intra-train feedback system for the CLIC interaction point is described. Results of luminosity performance simulations are presented and discussed for different scenarios of ground motion. We also show how the intra-train feedback system can help to relax the very tight tolerances of the vertical vibration on the CLIC final doublet quadrupoles.

Summary for ILC + CLIC

- **Well developed IP collision FB system designs for both ILC and CLIC**

- **Simulations demonstrate luminosity recovery capability**

- **Demonstrated prototypes with required performance parameters**

- **Progress on designing customised beamline components + optimising layout**

- **Systems applicable to jitter control throughout machine**

- **Also applicable at XFELs + rings**

Ground-motion feed forward

Compensation of orbit distortion due to quadrupole motion using feed-forward control at KEK ATF

D.R. Bett [a,*], C. Charrondière [a], M. Patecki [a], J. Pfingstner [a], D. Schulte [a], R. Tomás [a], A. Jeremie [b], K. Kubo [c], S. Kuroda [c], T. Naito [c], T. Okugi [c], T. Tauchi [c], N. Terunuma [c], P.N. Burrows [d], G.B. Christian [d], C. Perry [d]

[a] European Organization for Nuclear Research (CERN), Geneva 23, CH-1211, Switzerland
[b] Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France
[c] KEK and SOKENDAI, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[d] University of Oxford, Keble Road, OX1 3RH, UK

ARTICLE INFO

ABSTRACT

The high luminosity requirement for a future linear collider sets a demanding limit on the beam quality at the Interaction Point (IP). One potential source of luminosity loss is the motion of the ground itself. The resulting misalignments of the quadrupole magnets cause distortions to the beam orbit and hence an increase in the beam emittance. This paper describes a technique for compensating this orbit distortion by using seismometers to monitor the misalignment of the quadrupole magnets in real-time.

The first demonstration of the technique was achieved at the Accelerator Test Facility (ATF) at KEK in Japan. The feed-forward system consisted of a seismometer-based quadrupole motion monitoring system, an FPGA-based feed-forward processor and a stripline kicker plus associated electronics. Through the application of a kick calculated from the position of a single quadruple, the system was able to remove about 80% of the component of the beam jitter that was correlated to the motion of the quadrupole. As a significant fraction of the orbit jitter in the ATF final focus is due to sources other than quadrupole misalignment, this amounted to an approximately 15% reduction in the absolute beam jitter.
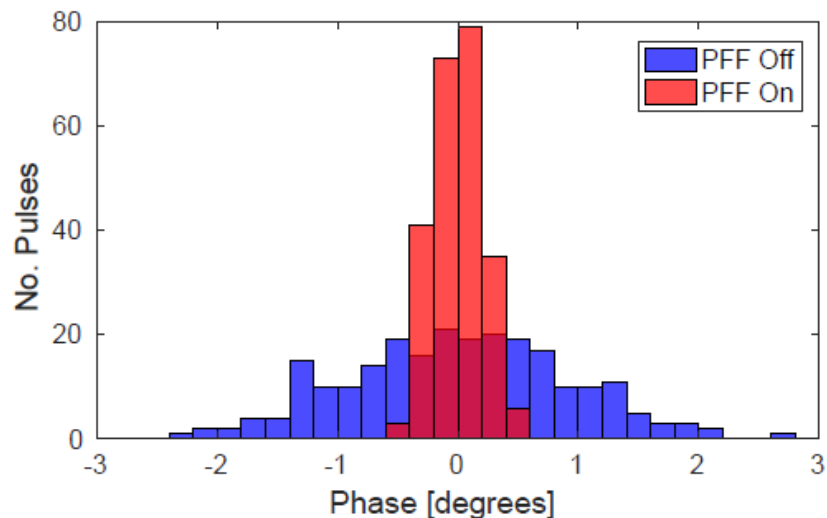
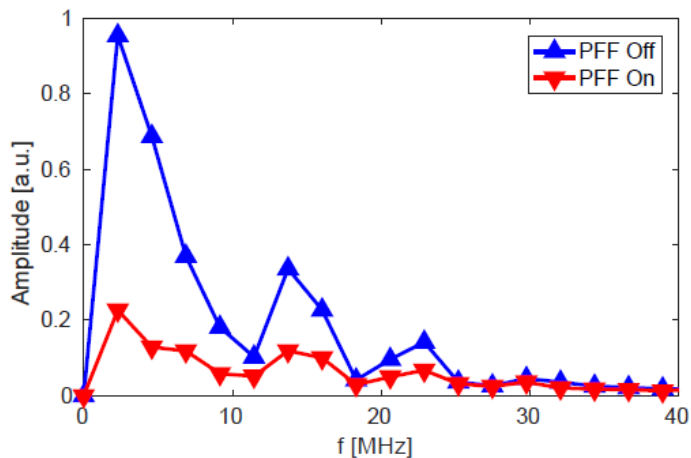# CLIC drive beam phase feed-forward Prototype at CTF3
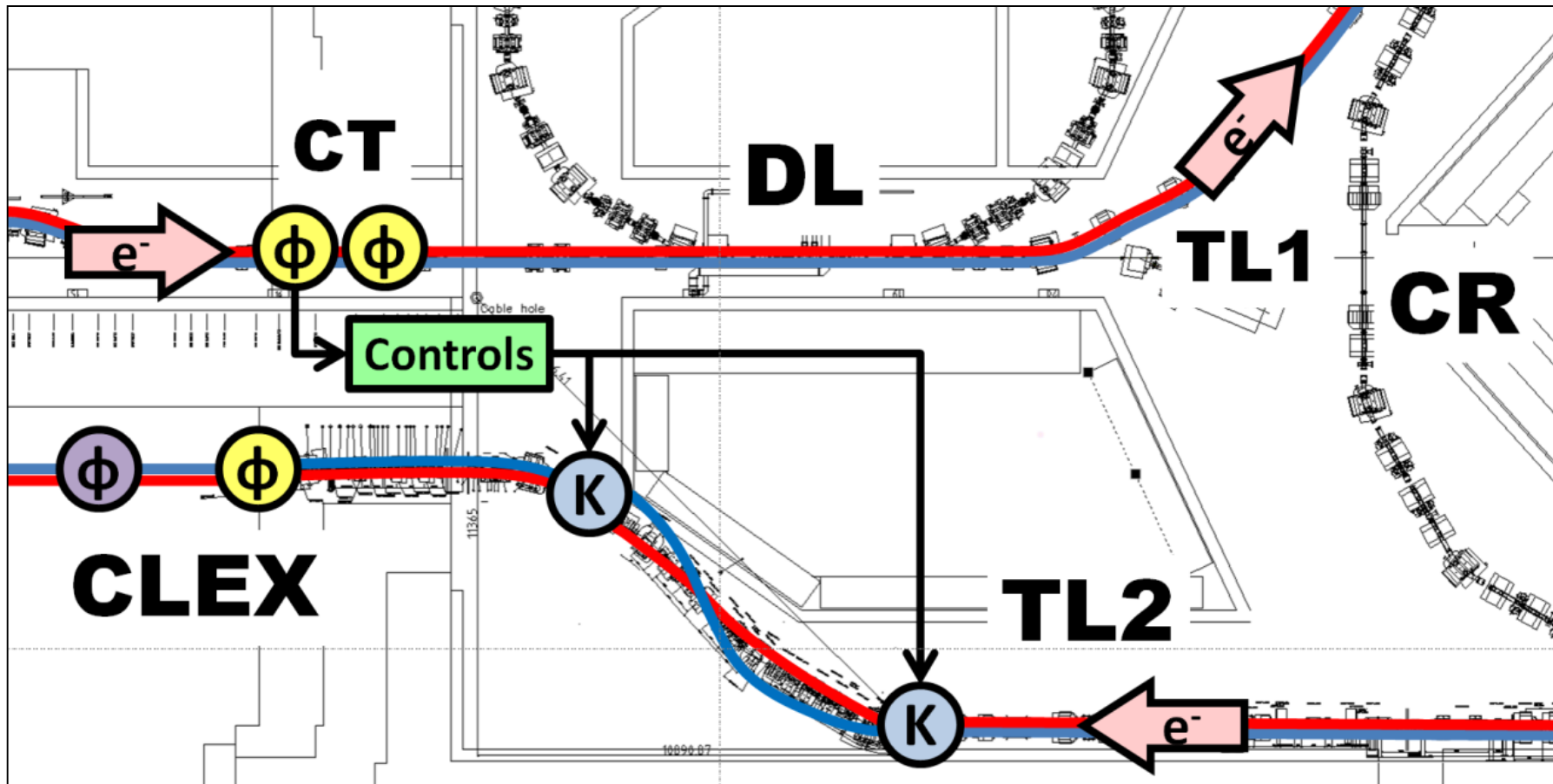
Closed-loop FF tests (Dec 2016)
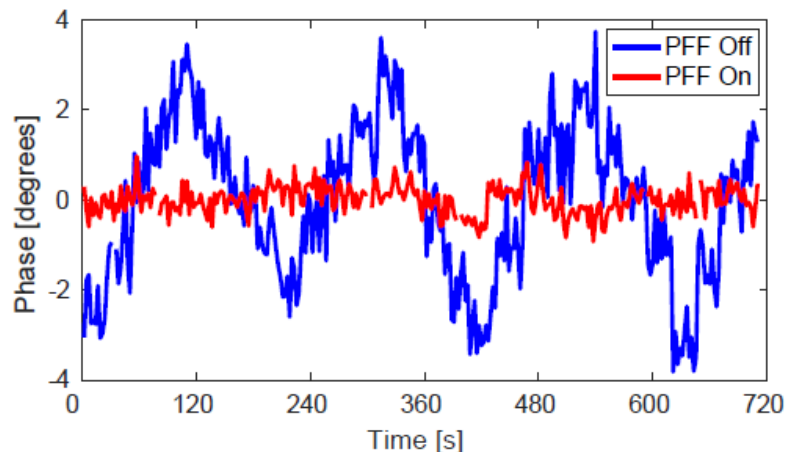
Correction of phase along pulse:
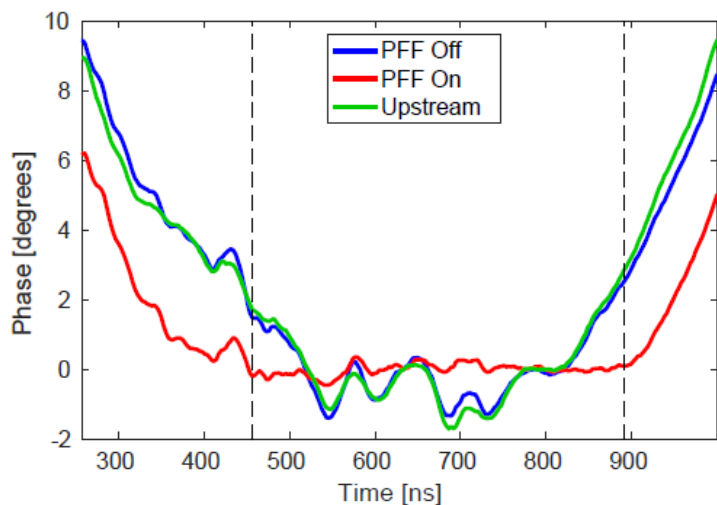
Reduction in mean phase jitter:

Performance vs. frequency:

Correction of induced errors:

CLIC phase feed forward

Stabilization of the arrival time of a relativistic electron beam to the 50 fs level

J. Roberts,[1,2] P. Skowronski,[2] P. N. Burrows,[1] G. B. Christian,[1] R. Corsini,[2]
A. Ghigo,[3] F. Marcellini,[3] and C. Perry[1]

[1]*John Adams Institute (JAI), University of Oxford, Denys Wilkinson Building, Keble Road,
Oxford OX1 3RH, United Kingdom*
[2]*The European Organization for Nuclear Research (CERN), Geneva 23 CH-1211, Switzerland*
[3]*Laboratori Nazionali di Frascati (LNFN), Via Enrico Fermi, 40, 00044 Frascati RM, Italy*

We report the results of a low-latency beam phase feed-forward system built to stabilize the arrival time of a relativistic electron beam. The system was operated at the Compact Linear Collider (CLIC) Test Facility (CTF3) at CERN where the beam arrival time was stabilized to approximately 50 fs. The system latency was 350 ns and the correction bandwidth > 23 MHz. The system meets the requirements for CLIC.

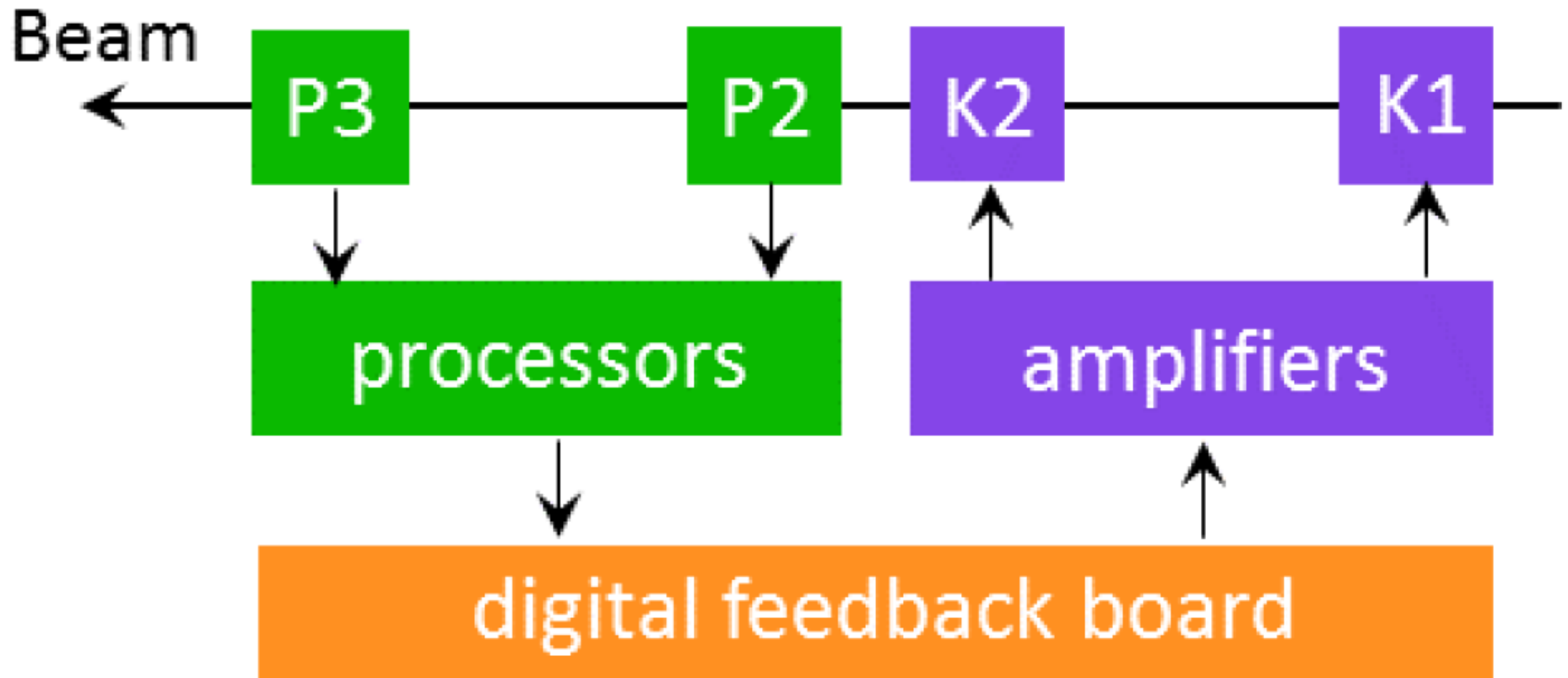# FONT5 installation at ATF2
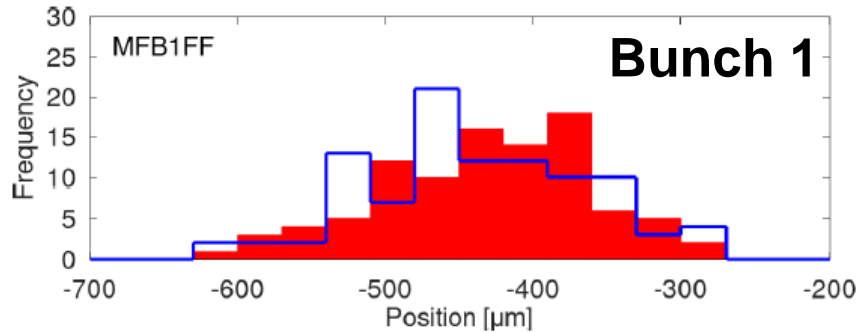
IP FB system
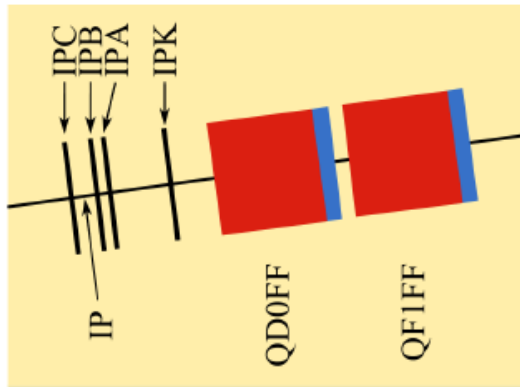
Upstream y-y' FB system
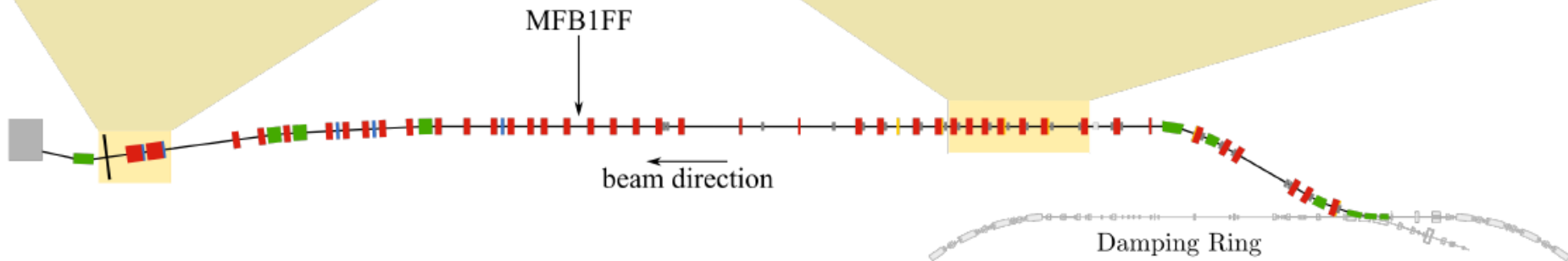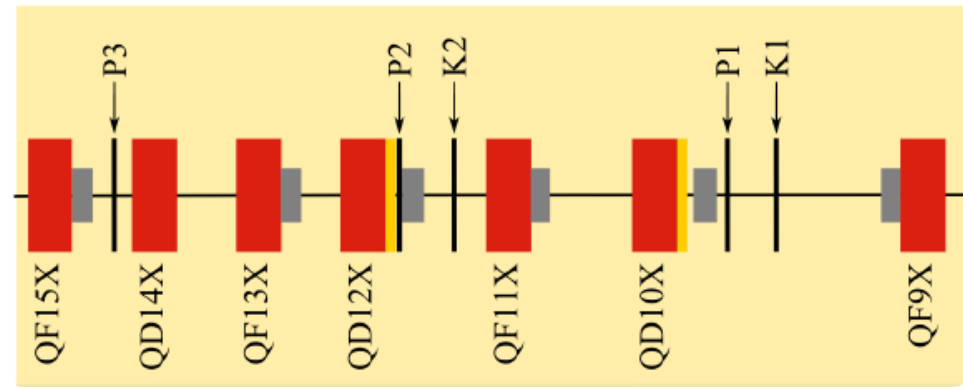
Upstream y-y' FB system

Upstream y-y' FB system

Witness BPMs

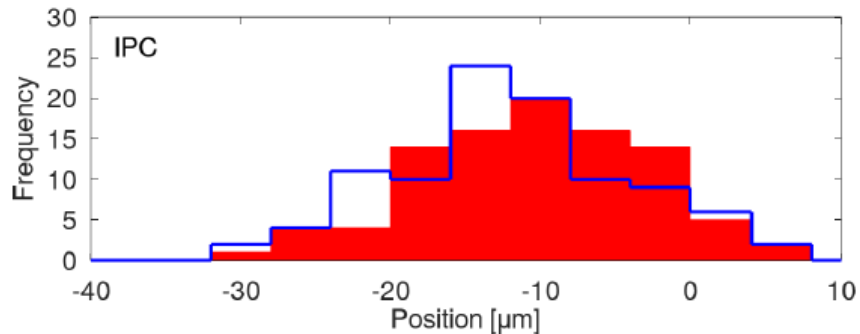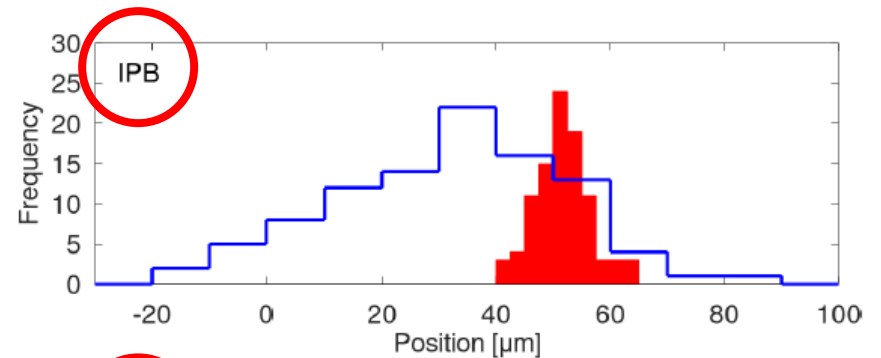**Jitter reduced by factor ~4 at IP**
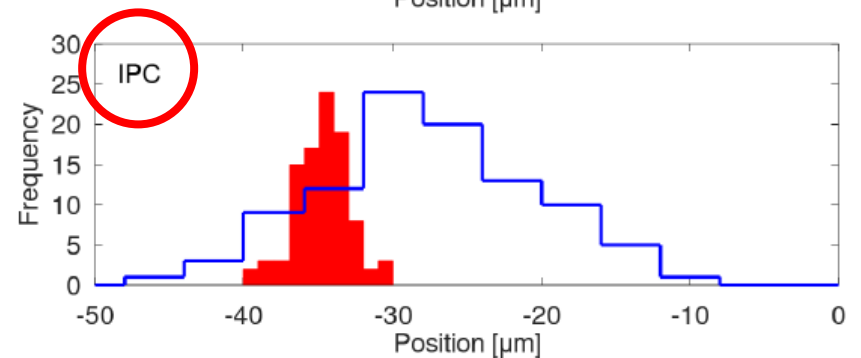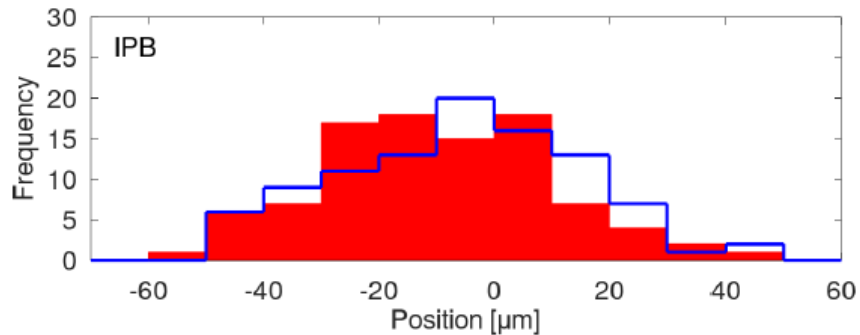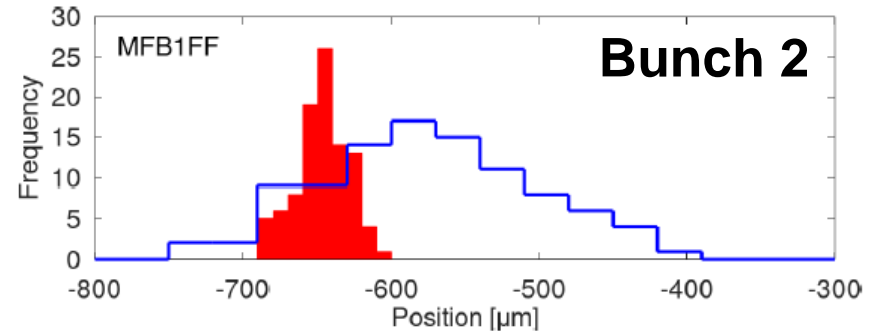
Wakefield effects reduced
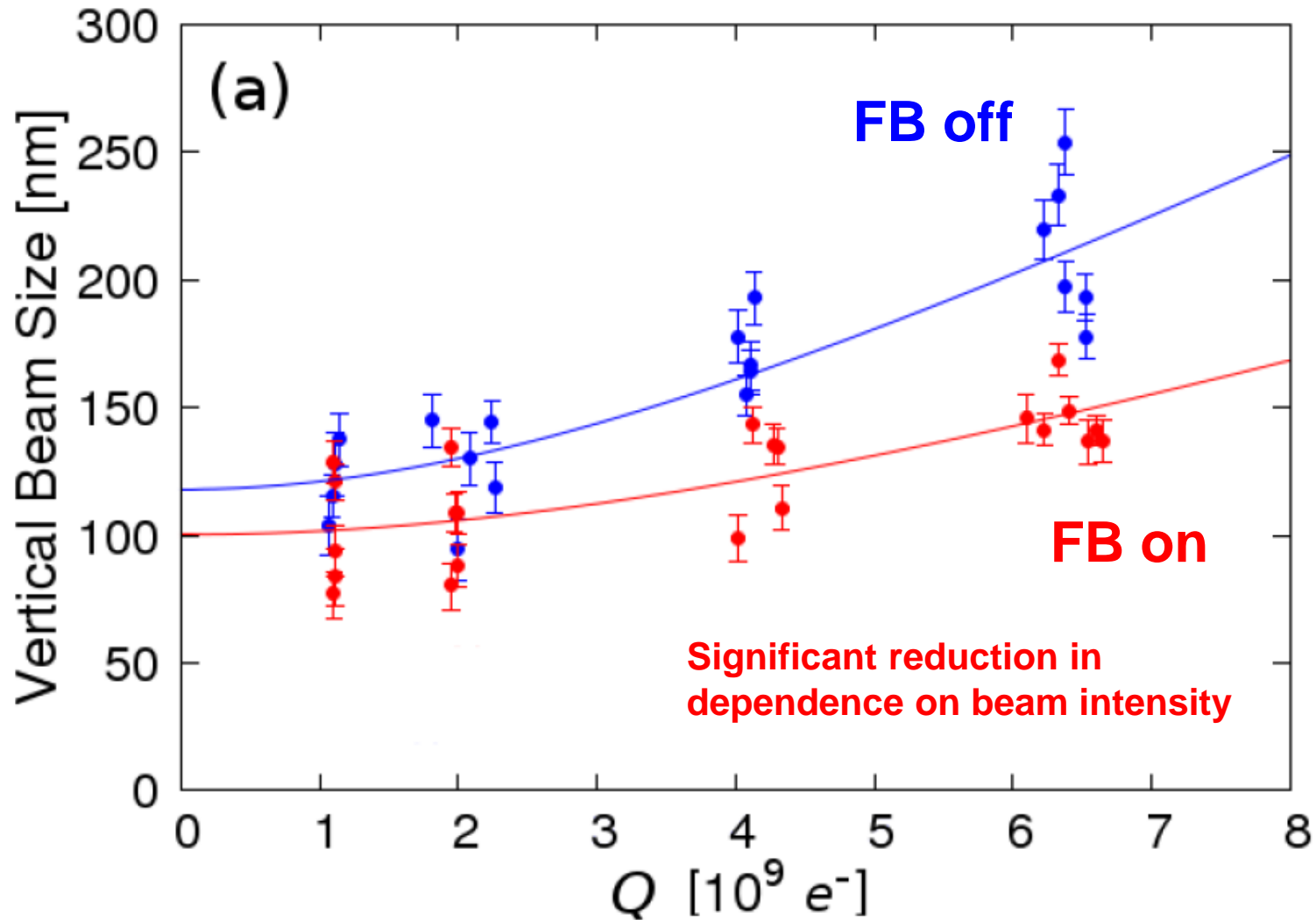
(a)

FB off

FB on

Significant reduction in dependence on beam intensity

Vertical Beam Size [nm] vs Q [10^9 e^-]

A sub-micron resolution, bunch-by-bunch beam trajectory feedback system and its application to reducing wakefield effects in single-pass beamlines

D.R. Bett,[a,1] P.N. Burrows,[a] C. Perry,[a] R. Ramjiawan,[a] N. Terunuma,[b] K. Kubo[b] and T. Okugi[b]

[a] *John Adams Institute for Accelerator Science at University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*
[b] *High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Japan*

E-mail: douglas.bett@physics.ox.ac.uk

ABSTRACT: A high-precision intra-bunch-train beam orbit feedback correction system has been developed and tested in the ATF2 beamline of the Accelerator Test Facility at the High Energy Accelerator Research Organization in Japan. The system uses the vertical position of the bunch measured at two beam position monitors (BPMs) to calculate a pair of kicks which are applied to the next bunch using two upstream kickers, thereby correcting both the vertical position and trajectory angle. Using trains of two electron bunches separated in time by 187.6 ns, the system was optimised so as to stabilize the beam offset at the feedback BPMs to better than 350 nm, yielding a local trajectory angle correction to within 250 nrad. The quality of the correction was verified using three downstream witness BPMs and the results were found to be in agreement with the predictions of a linear lattice model used to propagate the beam trajectory from the feedback region. This same model predicts a corrected beam jitter of c. 1 nm at the focal point of the accelerator. Measurements with a beam size monitor at this location demonstrate that reducing the trajectory jitter of the beam by a factor of 4 also reduces the increase in the measured beam size as a function of beam charge by a factor of c. 1.6.

Trajectory control of wakefield effects

Tracking beam to focal point

Track beam data from upstream region to IP using MADX model

→ **beam stabilised to ~1nm at IP**

→ **correction limited by upstream FB BPM resolution**

→ **not possible to measure directly with 1nm resolution!**
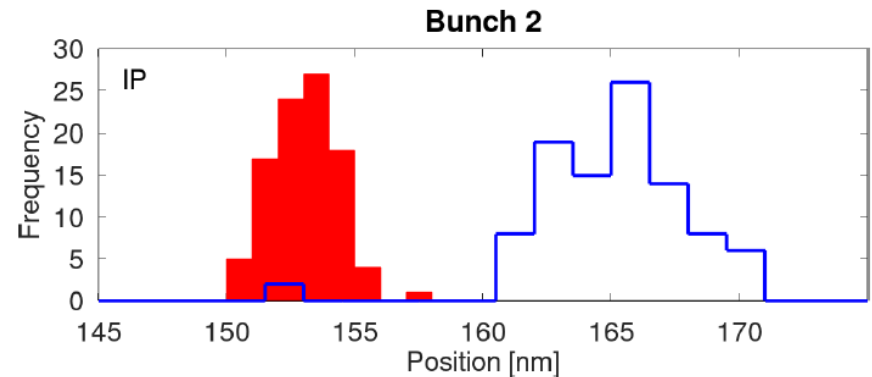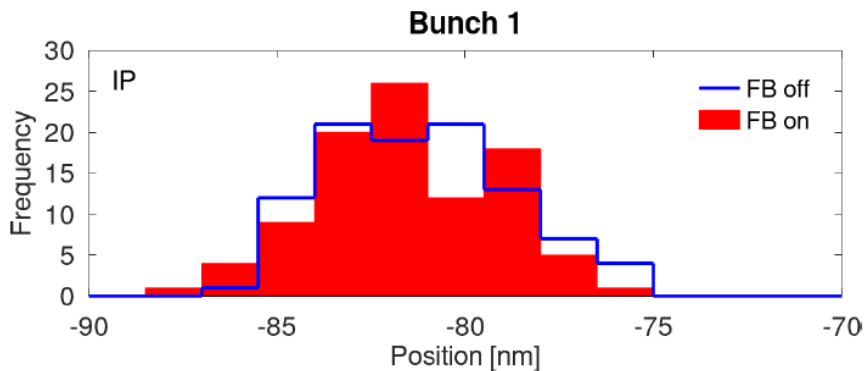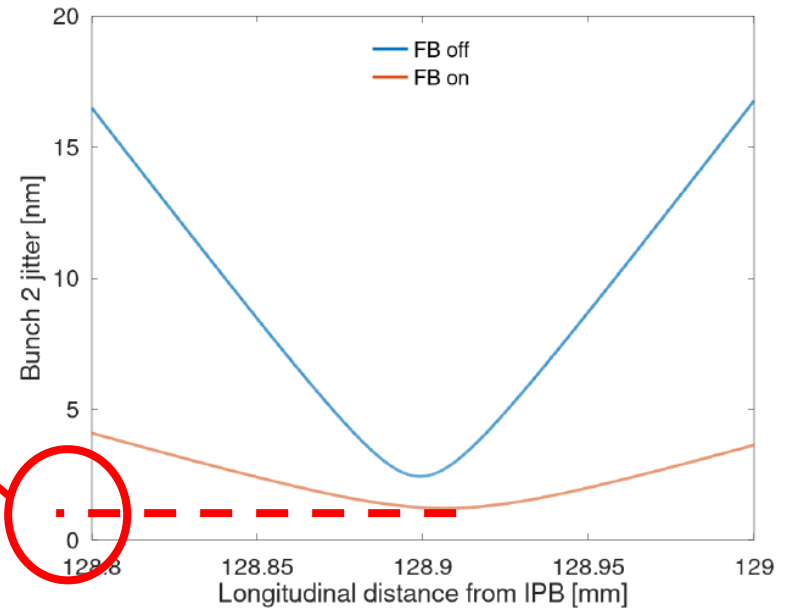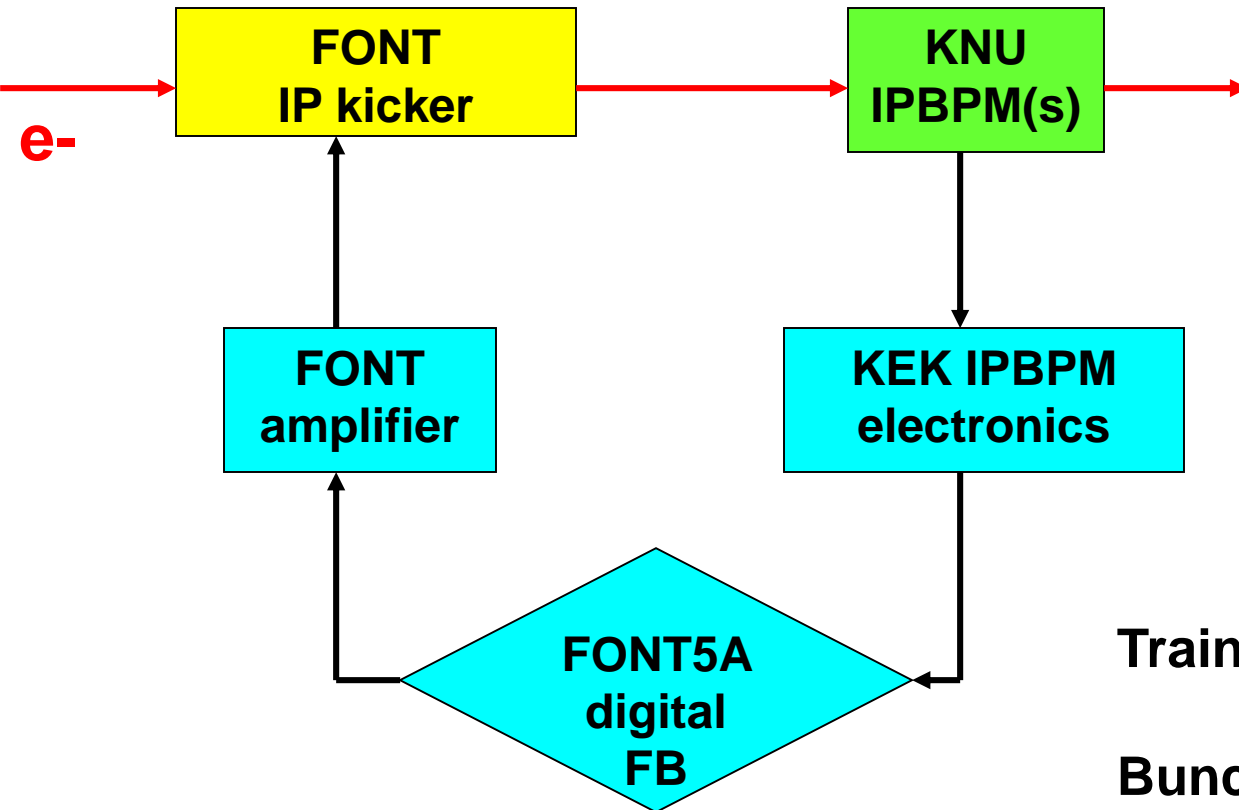
ATF2 'IP FB' system

ATF2 'IP FB' system

e-
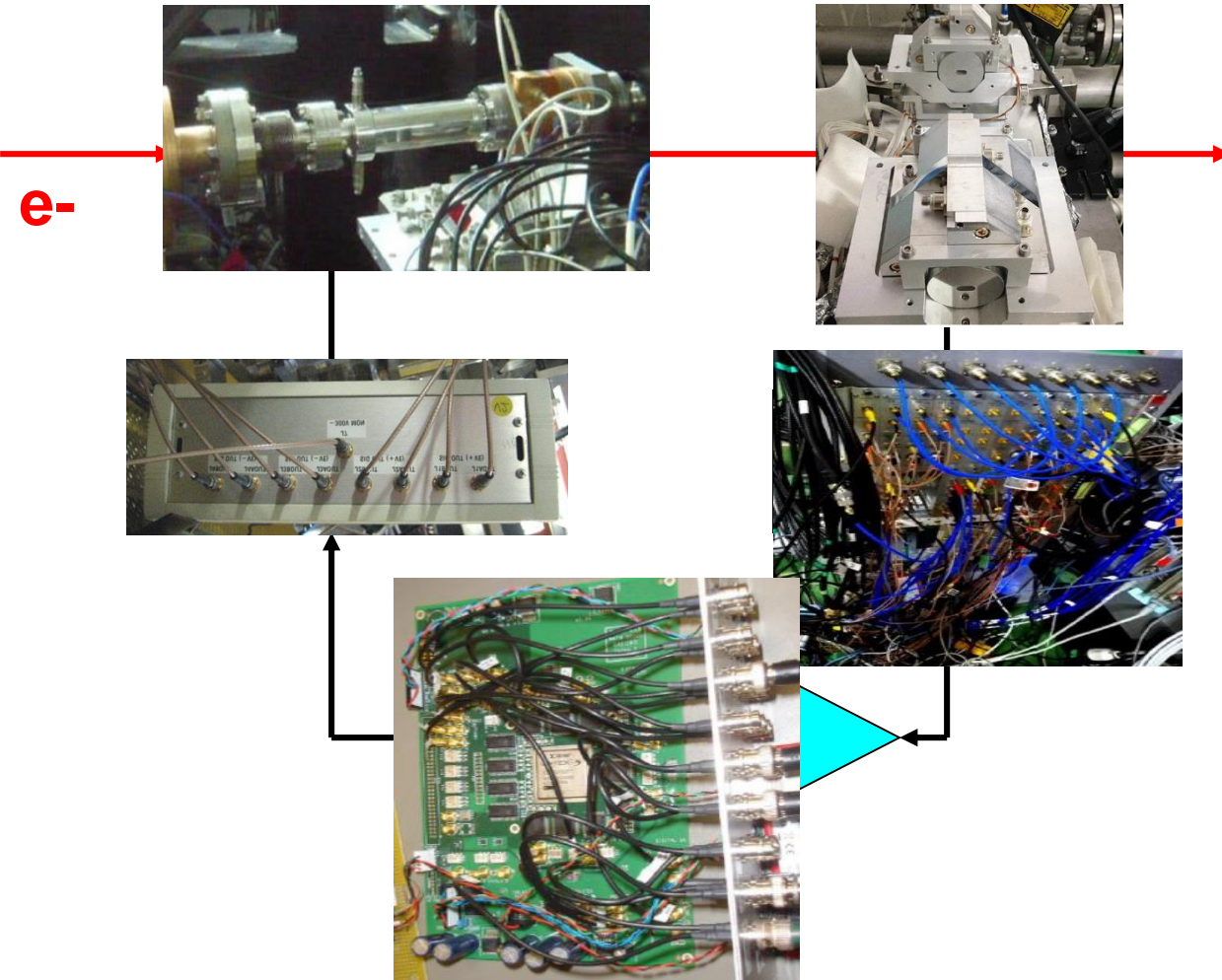
ATF2 'IP FB' results

- **Best real-time IPBPM resolution ~ 20 nm (< 25nm routine)**
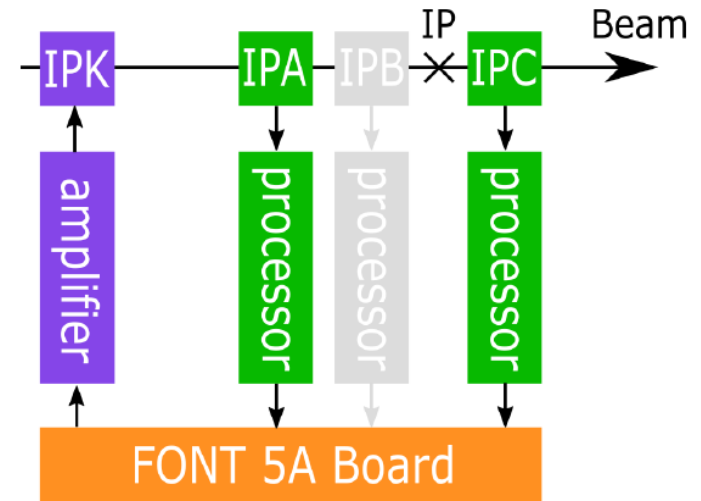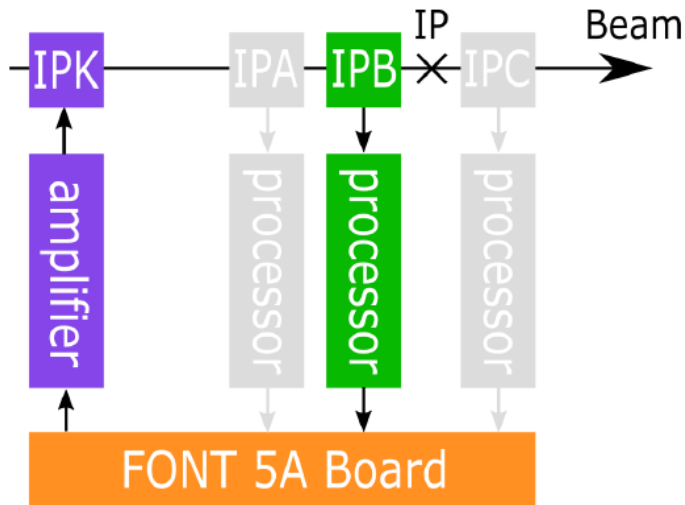
	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	109 ± 11	$11? \pm ?$
2	119 ± 12	50 ± 4

	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	106 ± 16	$10? \pm 1?$
2	96 ± 10	41 ± 4

- **Further improvements possible: stabilisation to ~ 25 nm?**

Thanks!

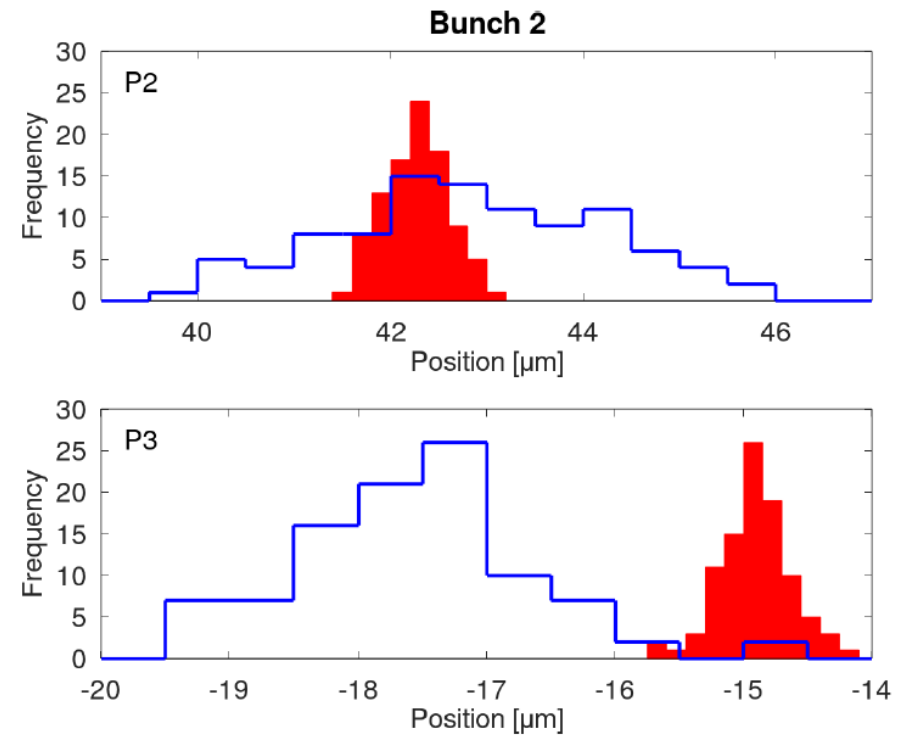|		
Jan Paszkiewicz	DPhil (2020)	Available soon
Eugenio Senes	DPhil (2020)	Development of a beam position monitor for co-propagating electron and proton beams
Chetan Gohil	DPhil (2020)	Dynamic Imperfections in the Compact Linear Collider
Pierre Korysko	DPhil (2020)	Intensity-dependent effects in the Accelerator Test Facility 2 and extrapolation to future electron-positron linear colliders
Rebecca Ramjiawan	DPhil (2019)	Development of feedback algorithms for future linear colliders
Talitha Bromwich	DPhil (2018)	Development of high-resolution cavity beam position monitors for use in low-latency feedback systems
Jack Roberts	DPhil (2016)	Development of a Beam-based Phase Feedforward Demonstration at the CLIC Test Facility (CTF3)
Davide Gamba	DPhil (2016)	Online optimisation of the CLIC Drive Beam bunch train recombination at CTF3
Neven Blaskovic Kraljevic	DPhil (2015)	Development of a high-precision low-latency position feedback system for single-pass beamlines using stripline and cavity beam position monitors
Michael Davis	DPhil (2014)	The Development of Intra-train Beam Stabilisation System Prototypes for a Future Linear Collider
Douglas Bett	DPhil (2013)	The development of a fast intra-train beam-based feedback system capable of operating on the bunch trains of the International Linear Collider
Alexander Gerbershagen	DPhil (2013)	CLIC Drive Beam Phase Stabilisation
Robert Apsimon	DPhil (2011)	The Development and Implementation of a Beam Position Monitoring System for use in the FONT Feedback System at ATF2
Ben Constance	DPhil (2011)	Design and beam testing of a fast, digital intra-train feedback system and its potential for application at the International Linear Collider
Christina Swinson	DPhil (2010)	Development of Beam Position Monitors for Final Focus Systems at the International Linear Collider
Christine Clarke	DPhil (2008)	The Interaction Point Collision Feedback System at the International Linear Collider and its Sensitivity to Expected Electromagnetic Backgrounds
Antony Hartin	PhD (2006)	Second Order QED Processes in an Intense Electromagnetic Field
Stephen Molloy	PhD (2006)	A Fast Feedback System Designed to Maintain Luminosity at a Linear Collider
Simon Jolly	DPhil (2003)	An Intra-pulse Fast Feedback System for a Future Linear Collider

Extra material

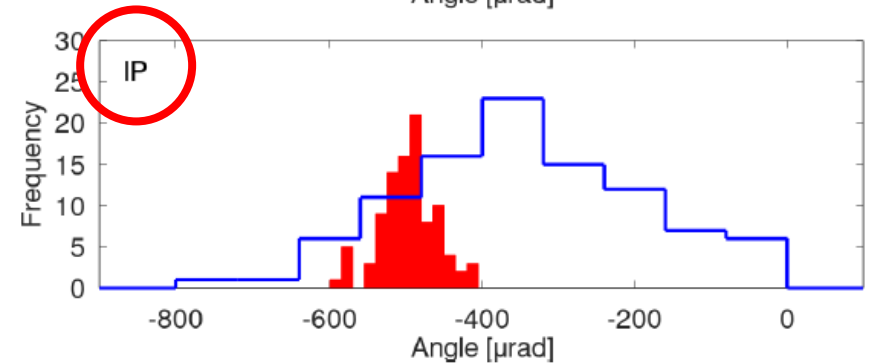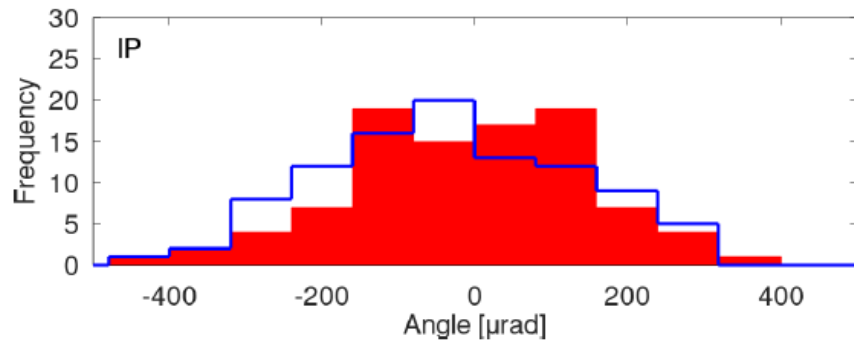# Upstream dual-phase FB system

In-loop BPMs
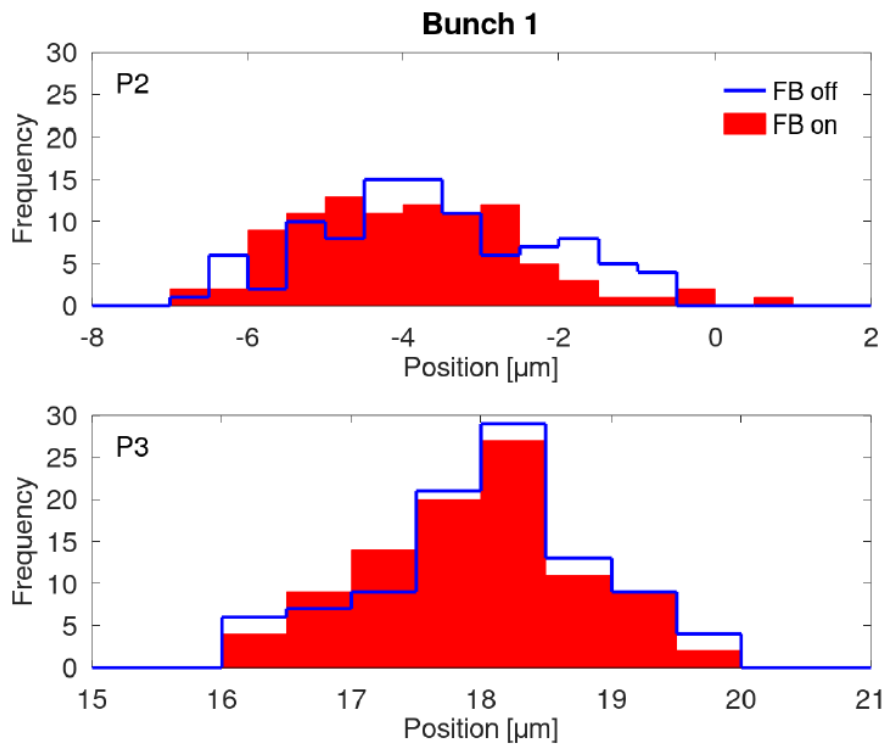
Jitter reduced by factor ~4, to BPM resolution (~200nm) limit

Upstream dual-phase FB system

Angle jitter reduced by factor ~4

5.712 GHz
Local Oscillator (LO)

$f_{LO(dip)}$ LO
$f_{LO(ref)}$ LO

6.426 GHz
(y-port)

6.426 GHz

714 MHz

~0 MHz

~0 MHz

First stage processing electronics – downmix to 714 MHz

Dipole cavity signal: 6.4 GHz signal dependent on vertical position and charge, is frequency down-mixed using an LO at 5.7 GHz.
Reference cavity signal: charge dependent, 6.4 GHz signal is frequency down-mixed using the same LO at 5.7 GHz.

Second stage processing electronics – downmix to baseband

Down-mixed dipole and reference signals at 714 MHz are mixed in-phase to produce the baseband **I signal**.
They are mixed in-quadrature to produce the baseband **Q signal**.

Digitisation of the BPM Waveform

- The waveforms I and Q are digitised at 357 MHz by ADCs on the FONT 5A board; these digitised samples are used to compute a bunch position:

$$y = \frac{1}{k}\left(\frac{I}{q}\cos\theta_{IQ} + \frac{Q}{q}\sin\theta_{IQ}\right),$$

where k and θ_{IQ} are determined through position calibration.

Single sample vs. integrated sample

- **Single sample**: only a single sample of each of the *I* and *Q* waveforms are used, resolution in this mode typically ~50 nm.

- **Integrated sample**: integration over a multi-sample window is used (up to 15 samples), this can improve the signal-to-noise ratio of the position measurement and consequently, the resolution. Resolution achieved in this mode of 20 nm.

- Improvements to the FONT system allow for feedback using multiple samples of the BPM waveforms.
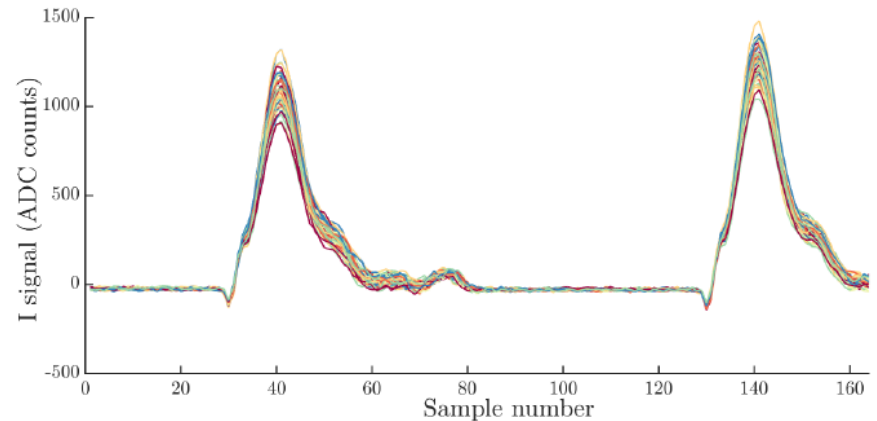
Example I signal waveform, in two bunch operation with 280 ns bunch spacing. Consecutive samples are separated by 2.8 ns.

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Real-time signal processing

- **Firmware runs on FPGA on digital board:**

  Digitisation of IPBPM I + Q waveforms

  Position determination by I,Q rotation + applying calibration

  Feedback calculation with gain application

  DAC output to drive kicker

  Must meet overall system latency < bunch spacing ~ 280ns

- **Standard version used single sample from 1 BPM as input**

- **Firmware upgraded (2018) to allow:**

  Real-time integration of up to 15 samples in BPM waveforms

  Input to FB loop from multiple BPMs

  → improved position resolution in real time

  → better FB stabilisation of beam

  FB loop latency measured ~ 232 ns

Outstanding Engineering Issues

- **Component designs need to be optimised for tight spatial environments**

- **Routing of cables**

- **Operation of (ferrite) devices in large, spatially-varying B-field**

- **Further studies of radiation environment**

- **Electronics location, rad hardness, shielding**

- **RF interference: beam ←→ FB electronics**

  kicker ←→ detector