ATF2 FONT Fast Feedback Systems

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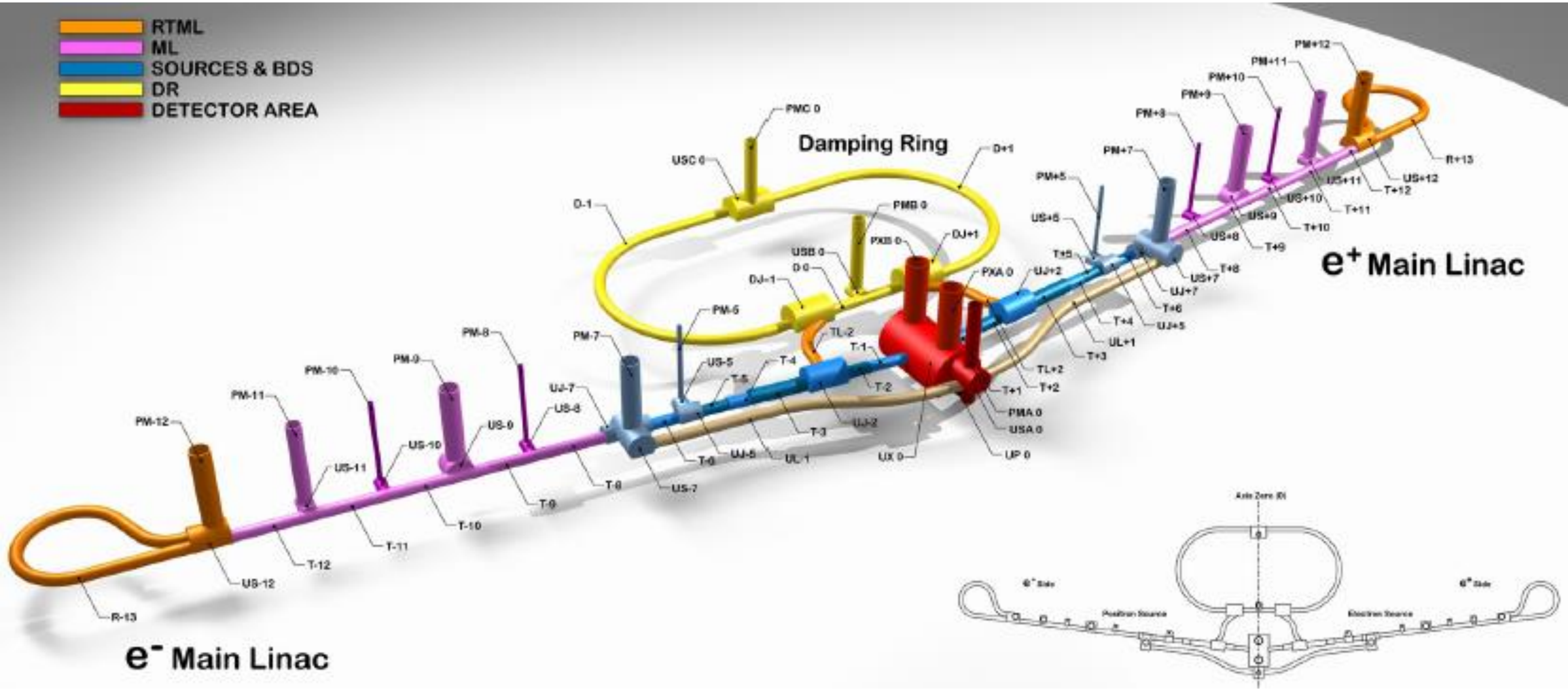
John Adams Institute

Oxford University

Outline

- **ILC IP FB prototype (FONT4)**
- **Dual-phase upstream FB system (FONT5)**
- **ATF2 IP FB system**
- **Summary + outlook**

International Linear Collider



Beam parameters

	ILC 250	
Electrons/bunch	2	10**10
Bunches/train	1312	
Bunch separation	554	ns
Train length	727	us
Train repetition rate	5	Hz
Horizontal IP beam size	516	nm
Vertical IP beam size	$\boxed{8}$	nm
Luminosity	1.4	10**34

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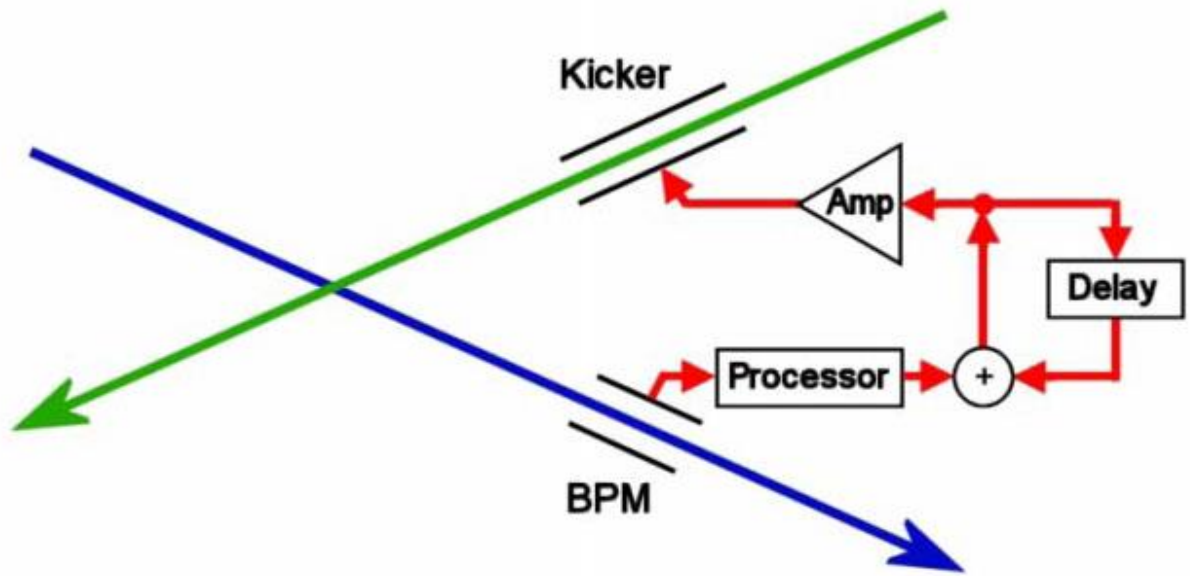
IP beam feedback concept

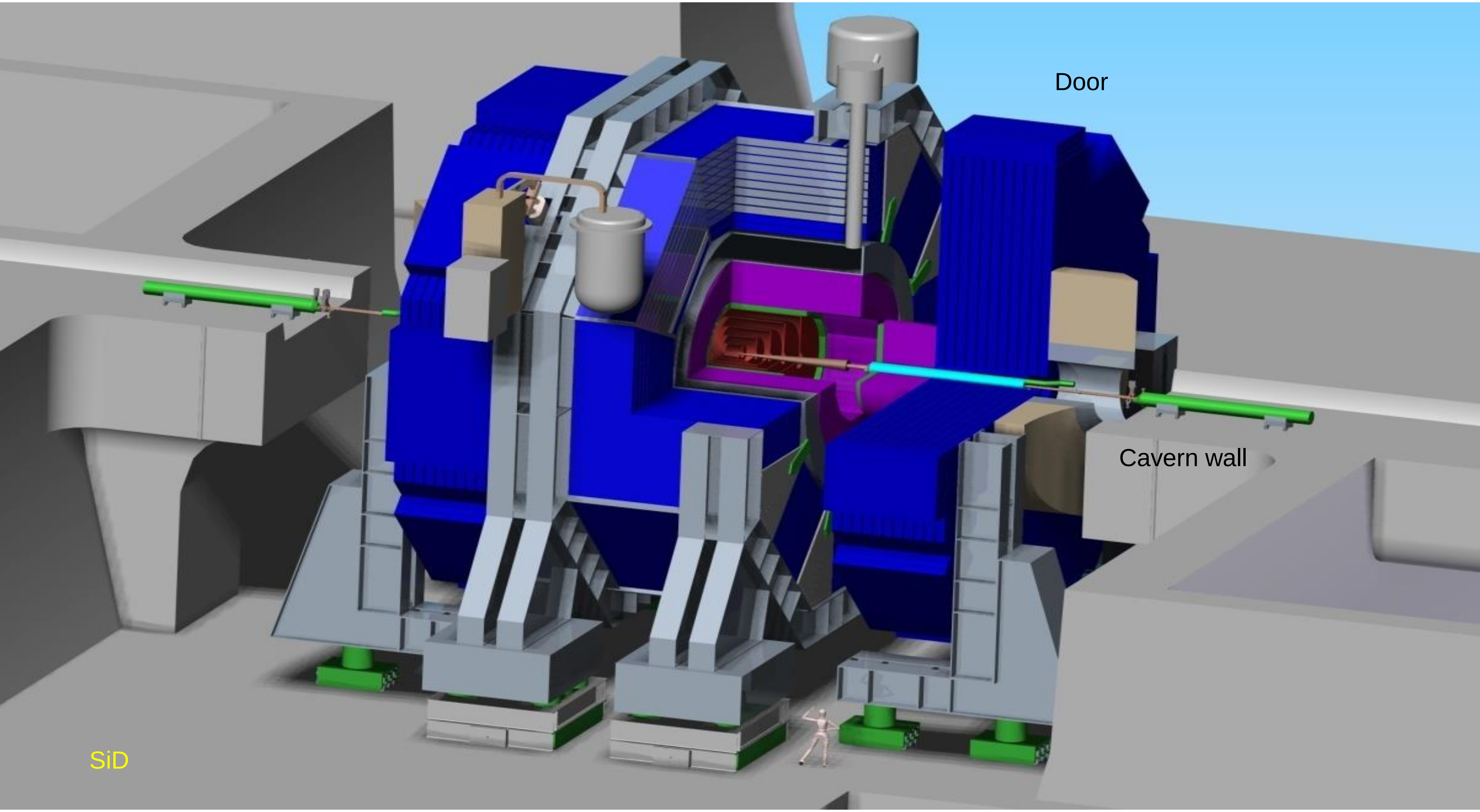
- Last line of defence against relative beam misalignment
- Measure vertical position of outgoing beam and hence beam-beam kick angle
- Use fast amplifier and kicker to correct vertical position of beam incoming to IR



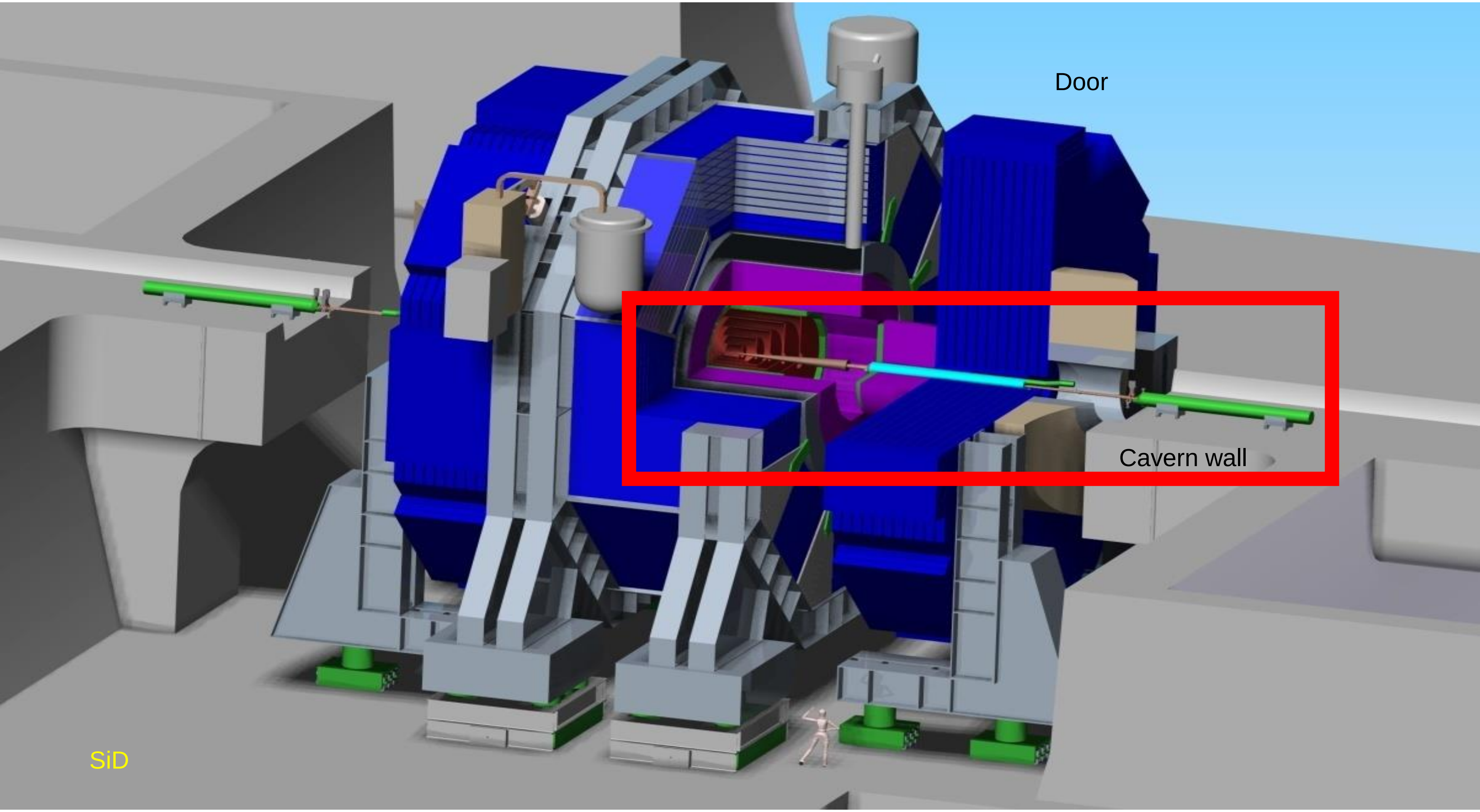
FONT – Feedback On Nanosecond Timescales:

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

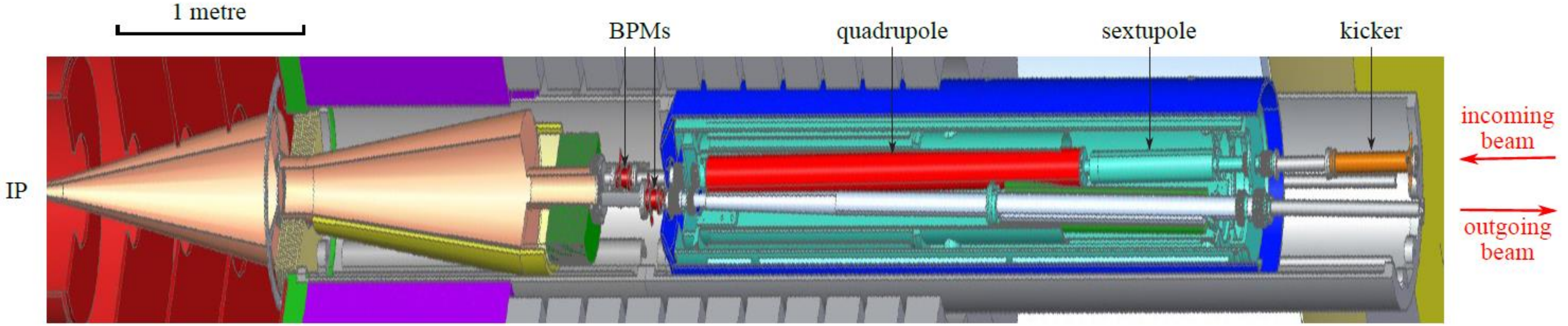
ILC Interaction Region (SiD)



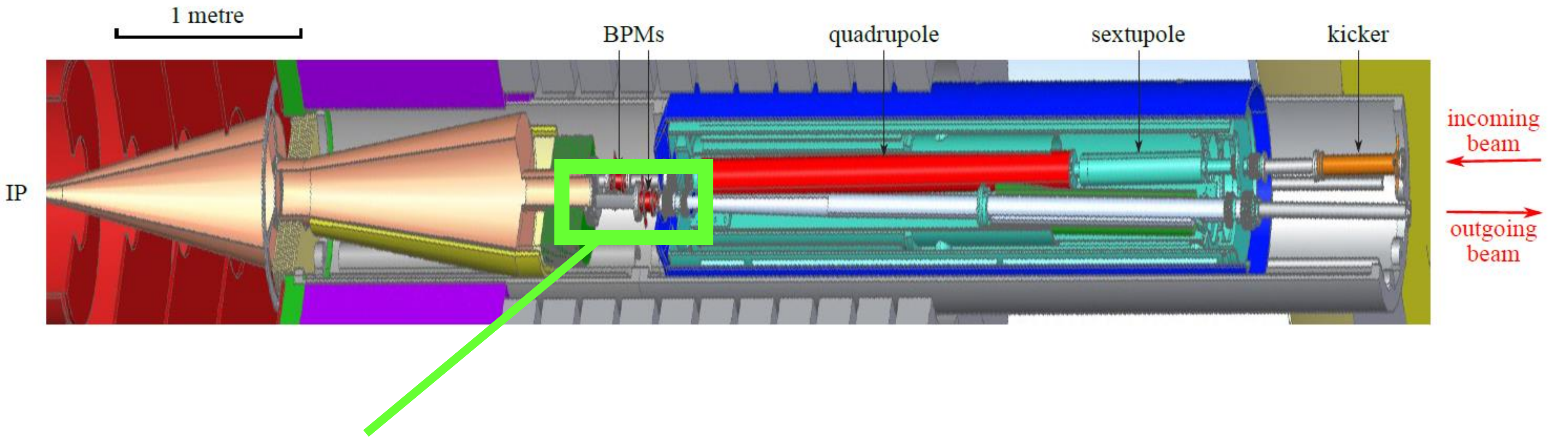
ILC Interaction Region (SiD)



Final-focus region (SiD)



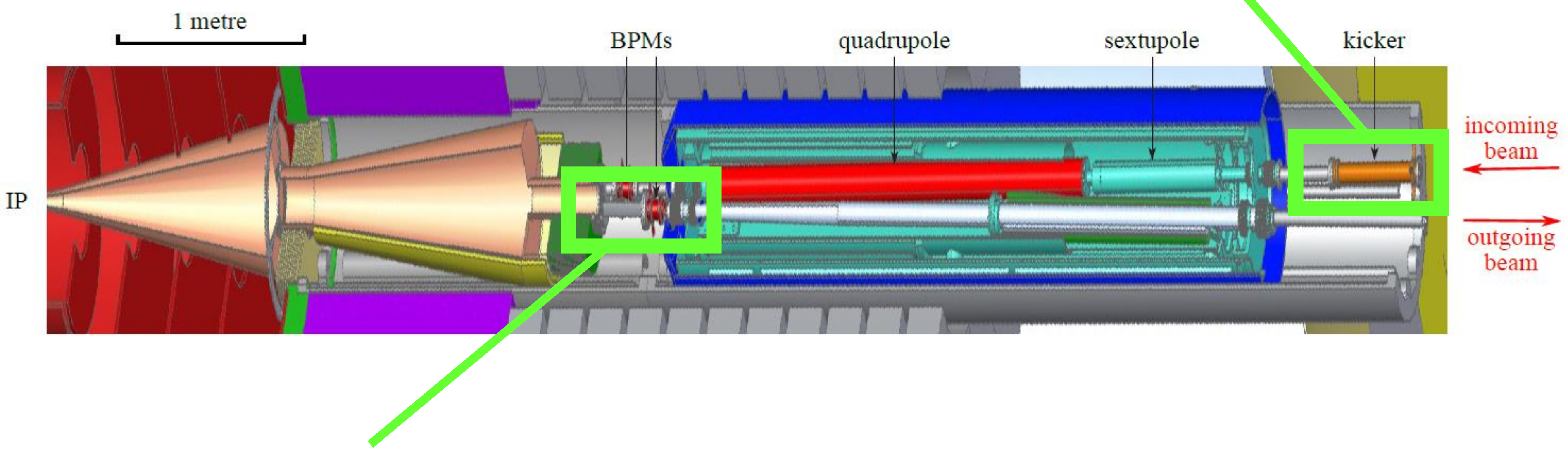
Final-focus region (SiD)



FB BPM on outgoing beamline

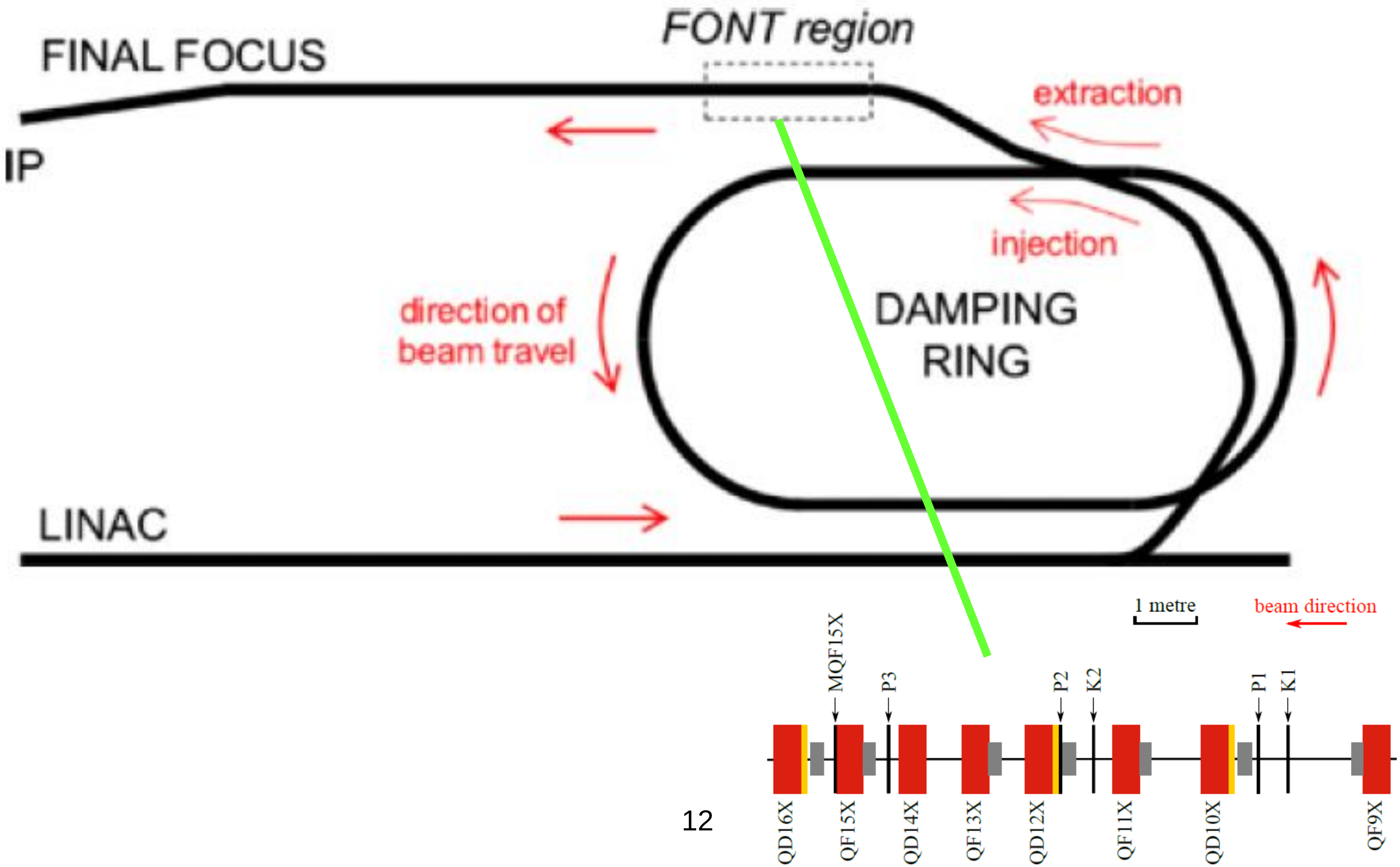
Final-focus region (SiD)

FB kicker on incoming beamline

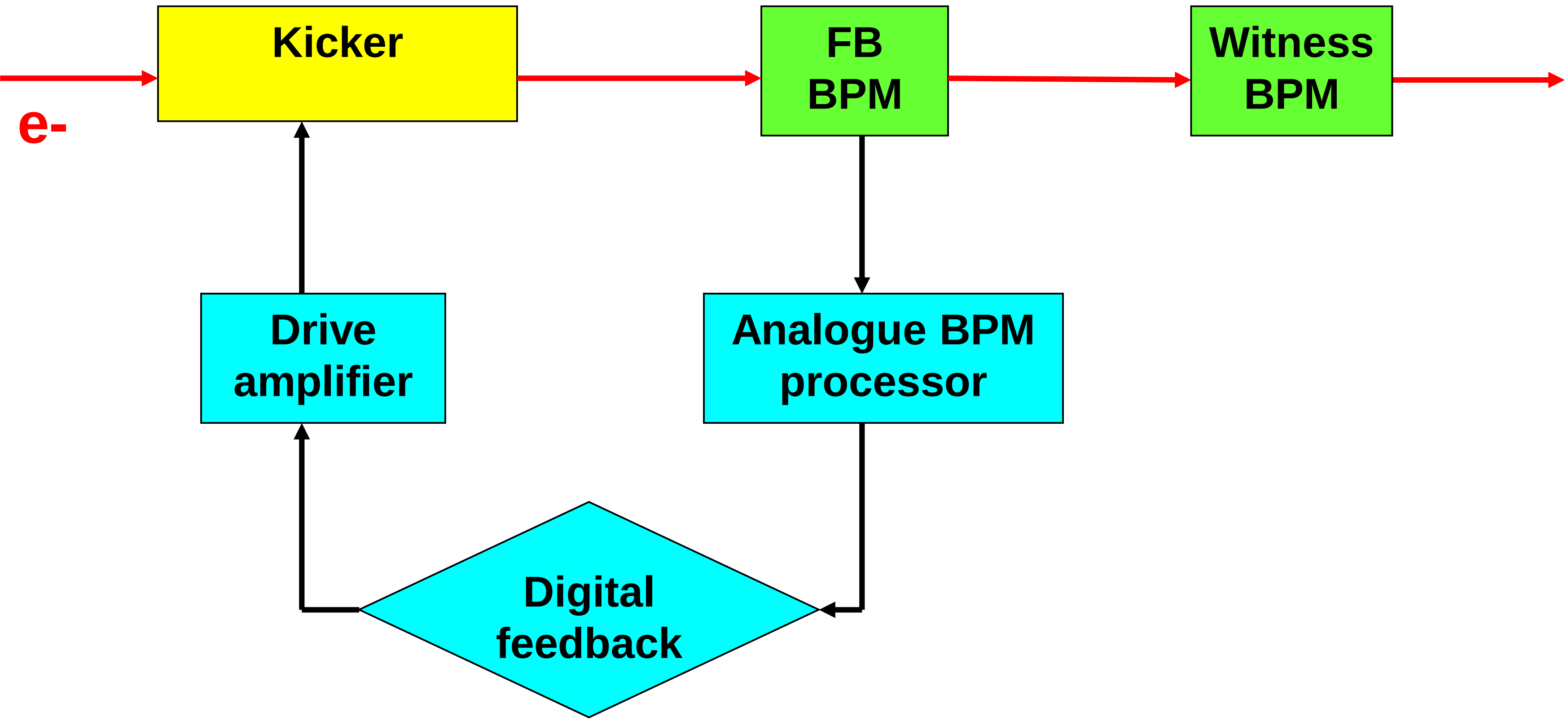


BPM on outgoing beamline

KEK Accelerator Test Facility (ATF2)



ILC IP FB prototype: FONT4 at ATF2



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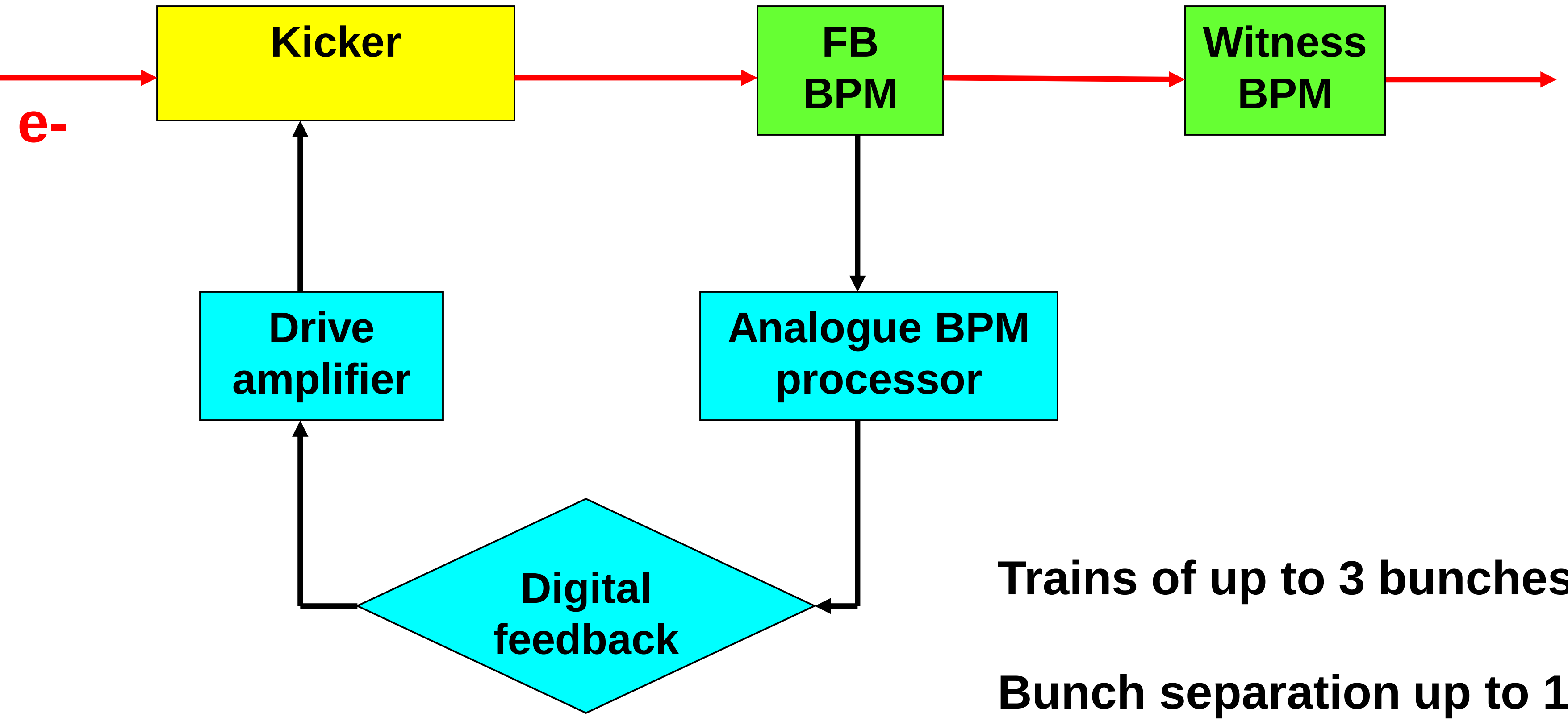
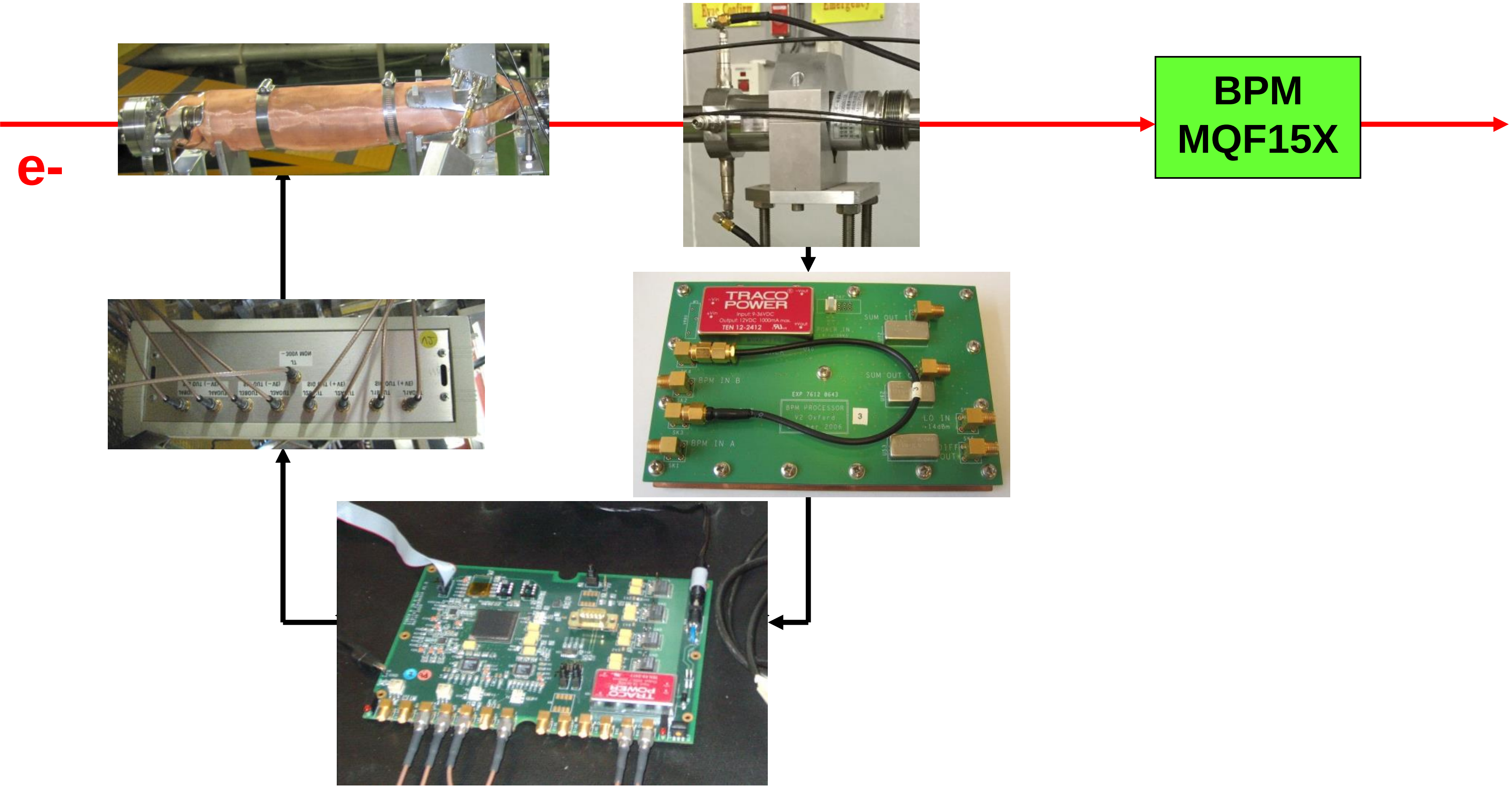


Trains of up to 3 bunches

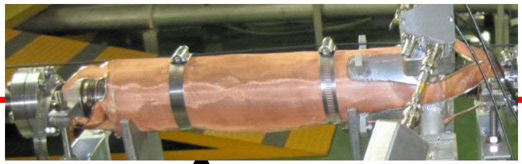
Bunch separation up to 154ns

ILC IP FB prototype: FONT4 at ATF2

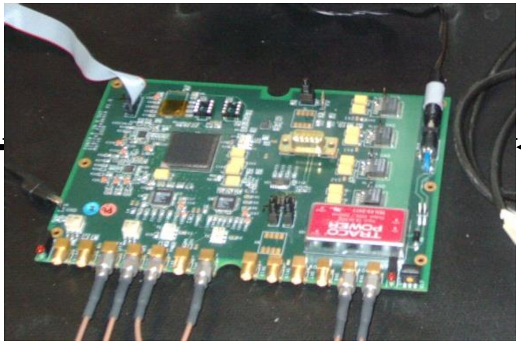


ILC IP FB prototype: FONT4 at ATF2

e-

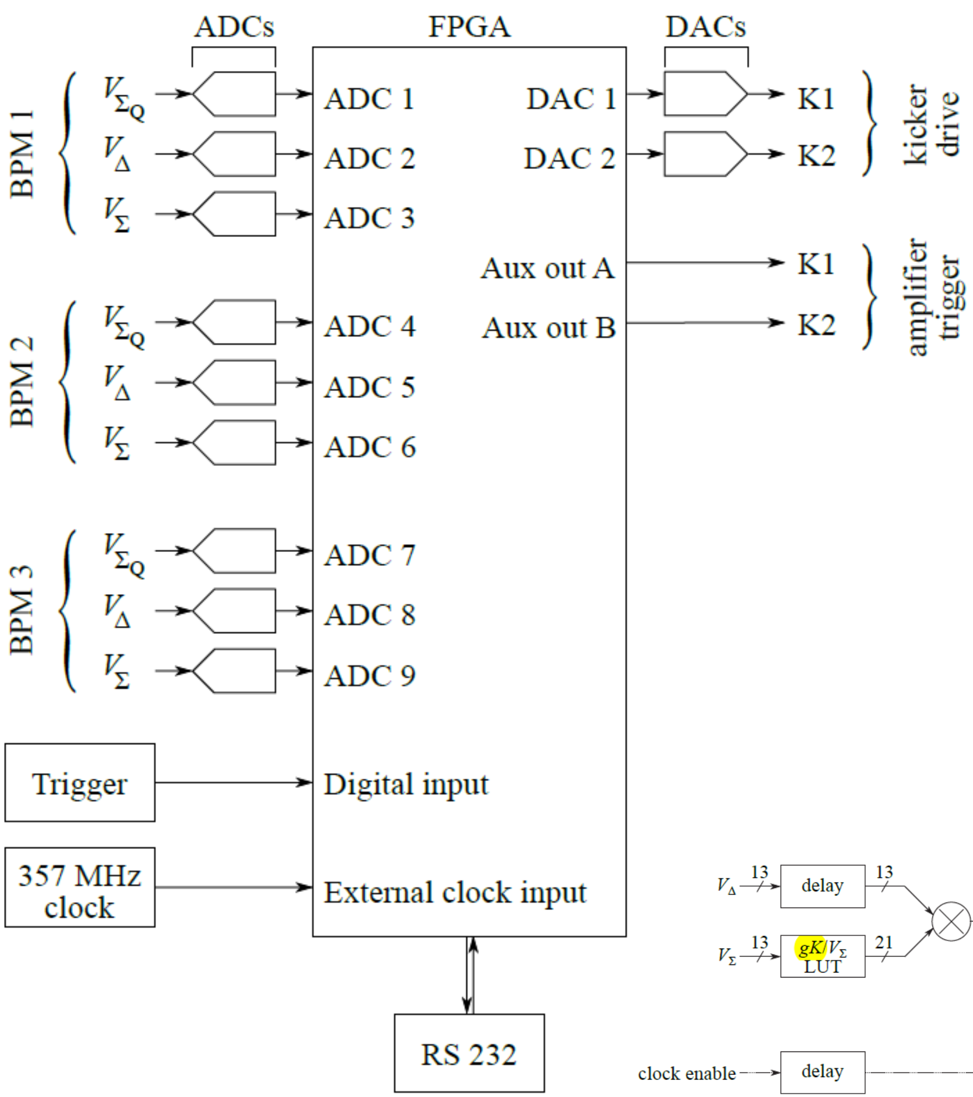


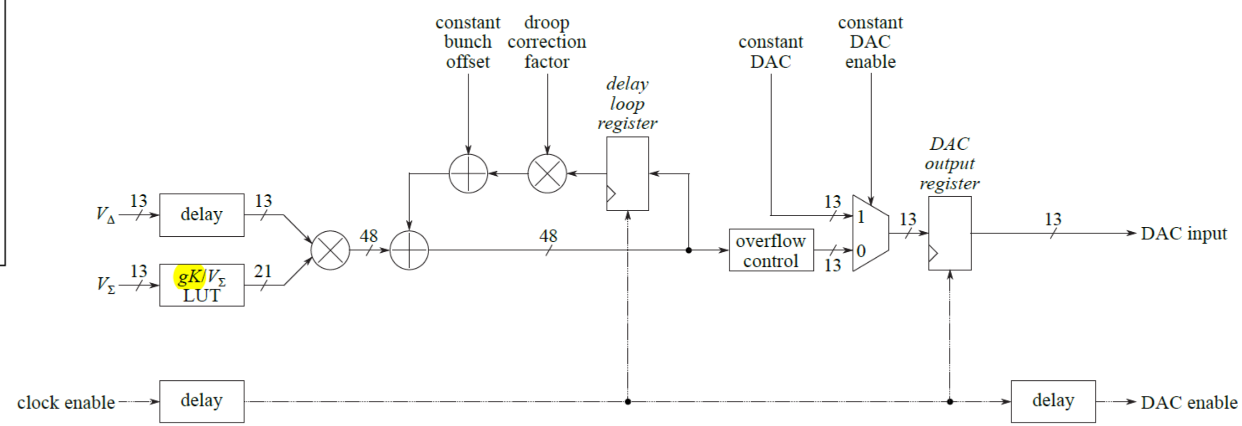
BPM MQF15X



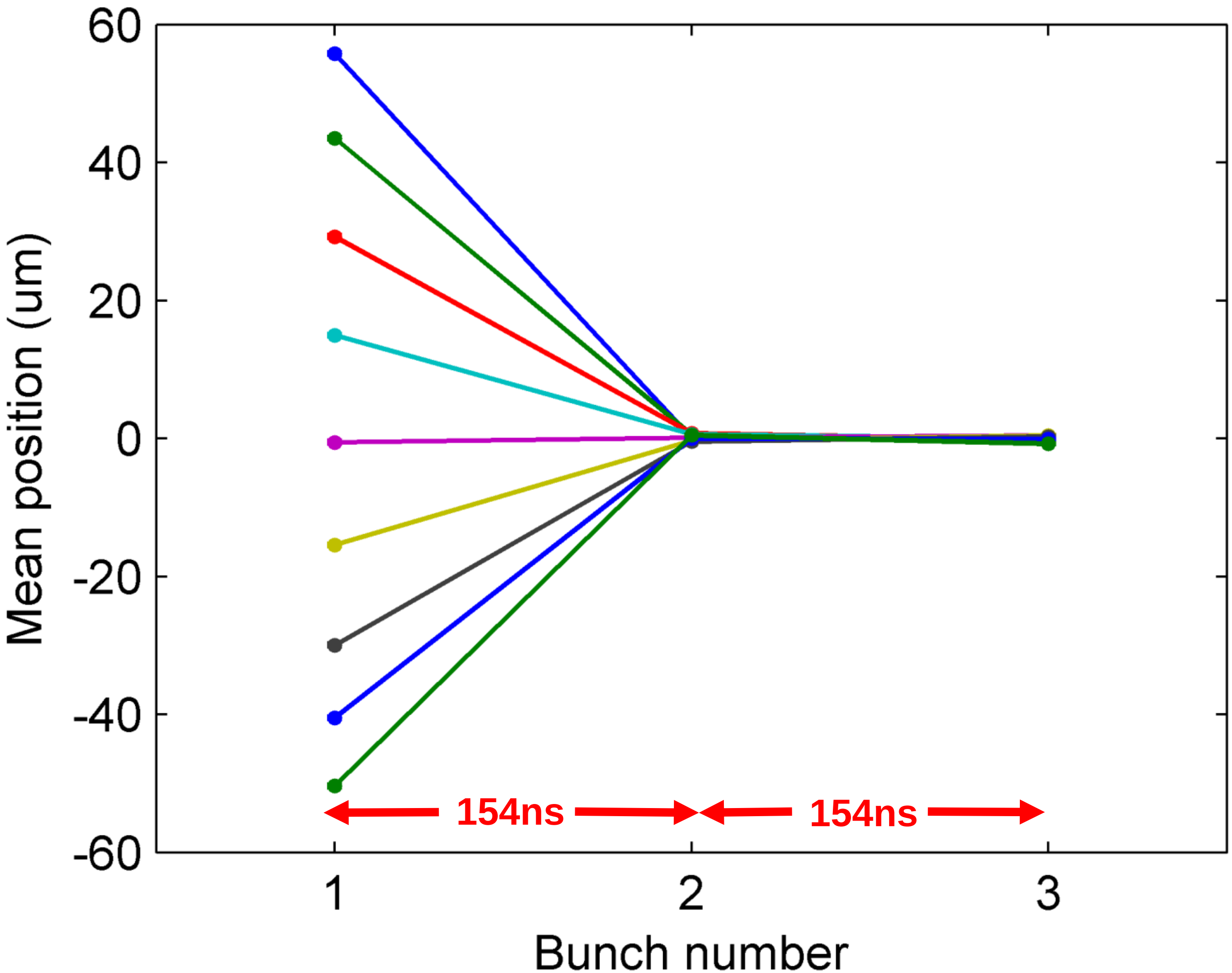
BPM resolution	~ 0.2um
Latency	~ 150ns
Drive power	> 300nm @ ILC

FONT digital feedback board





FONT4 performance



FONT4 performance

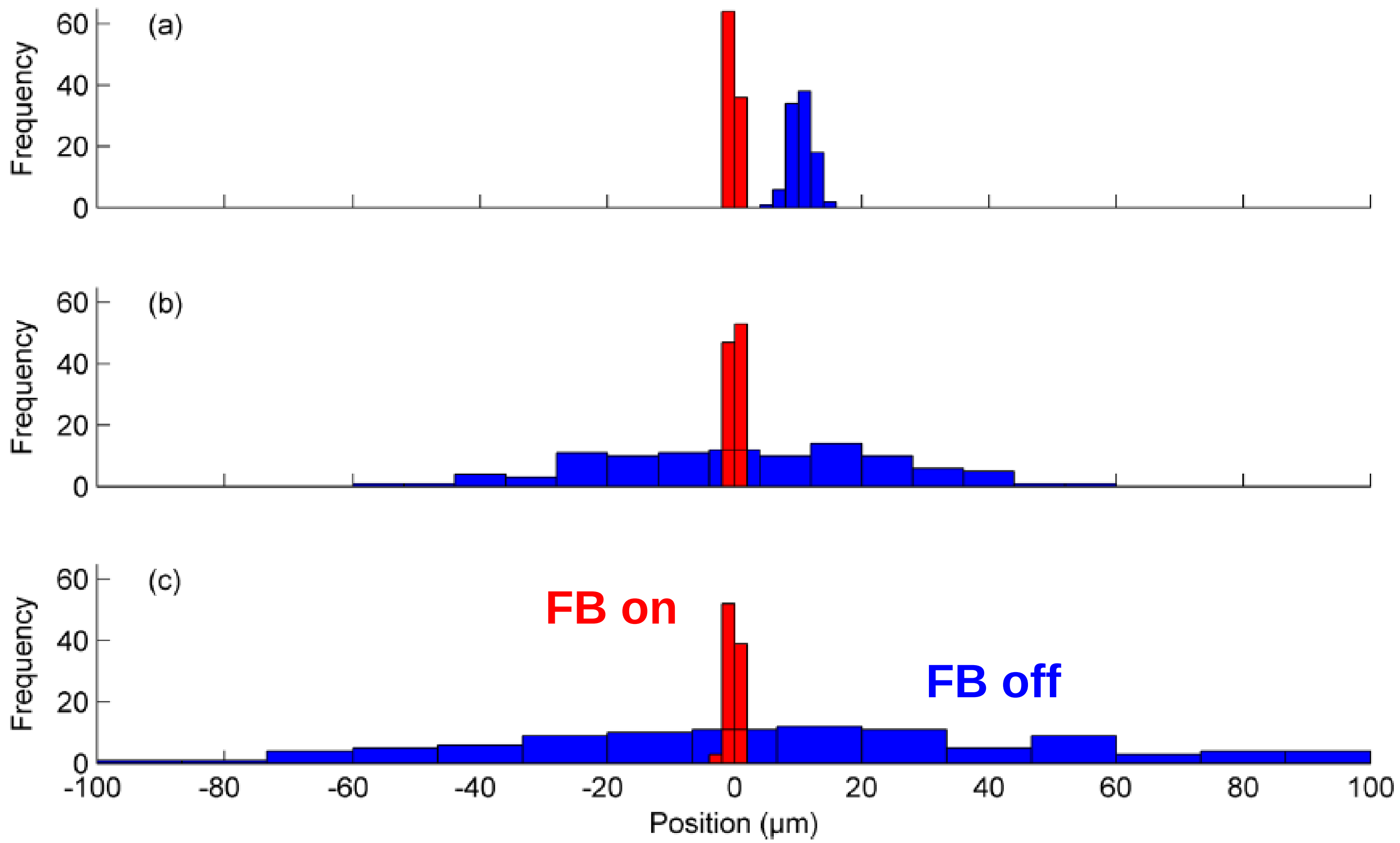


FIG. 19. Distributions of positions with feedback off (blue) and feedback on (red) for bunch 2 at P3 with incoming, uncorrected position jitters of (a) ~2 μm, (b) ~22 μm, and (c) ~45 μm.

FONT4 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	$\sim \pm60$	$\sim \pm180^\dagger$

† scaled by the ATF/ILC beam energy ratio

FB BPM paper

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 032803 (2015)

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.

DOI: 10.1103/PhysRevSTAB.18.032803 PACS numbers: 29.27.Fh, 41.85.Qg, 41.75.Ht, 29.20.db

ILC IP FB prototype paper

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 122802 (2018)

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

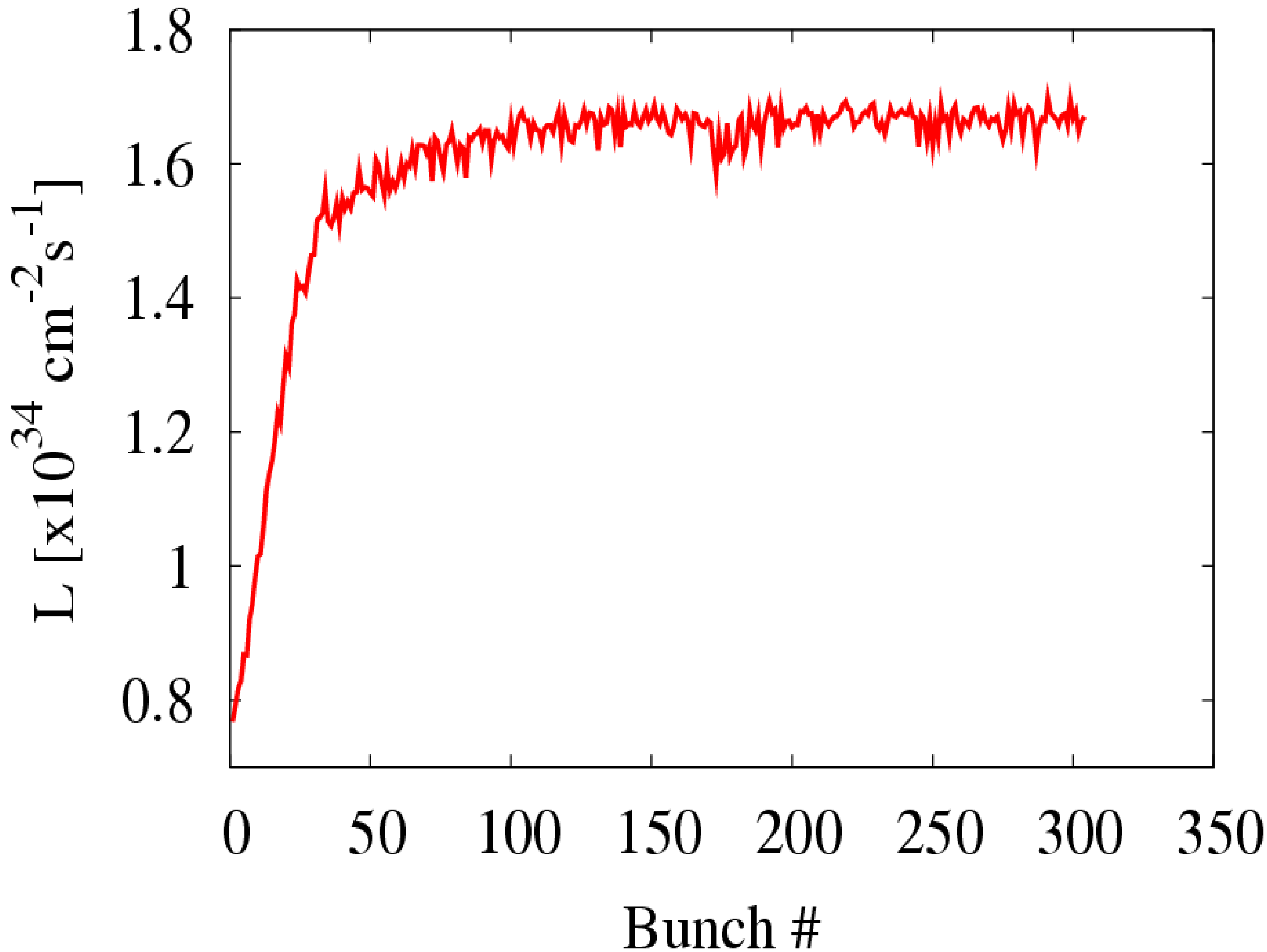
R. J. Apsimon,[*] D. R. Bett, N. Blaskovic Kraljevic,[†] R. M. Bodenstein, T. Bromwich, P. N. Burrows, G. B. Christian,[‡] B. D. Constance, M. R. Davis, C. Perry, and R. Ramjiawan
John Adams Institute for Accelerator Science at University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom

(Received 13 December 2017; published 17 December 2018)

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

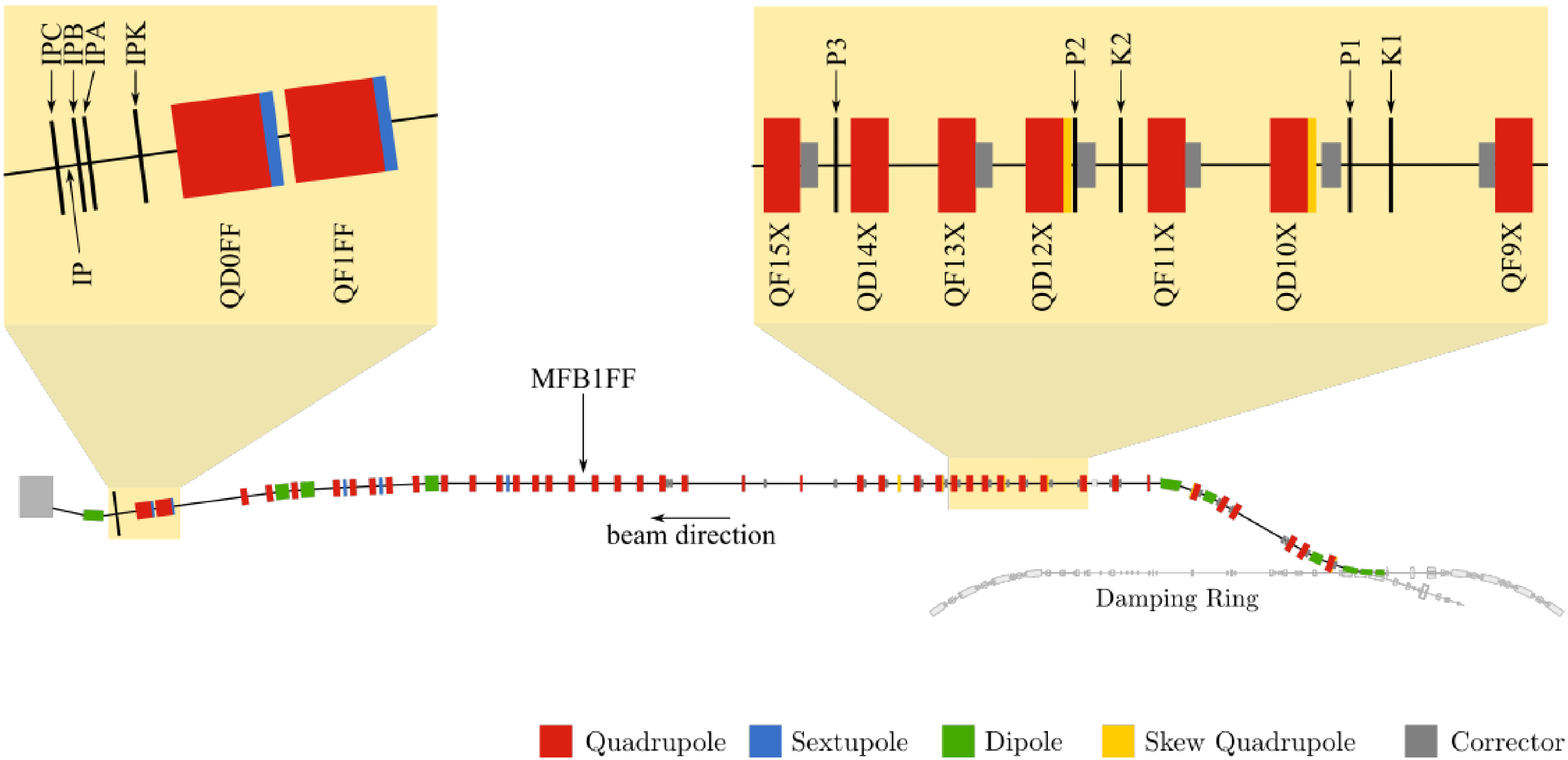
(500 GeV)



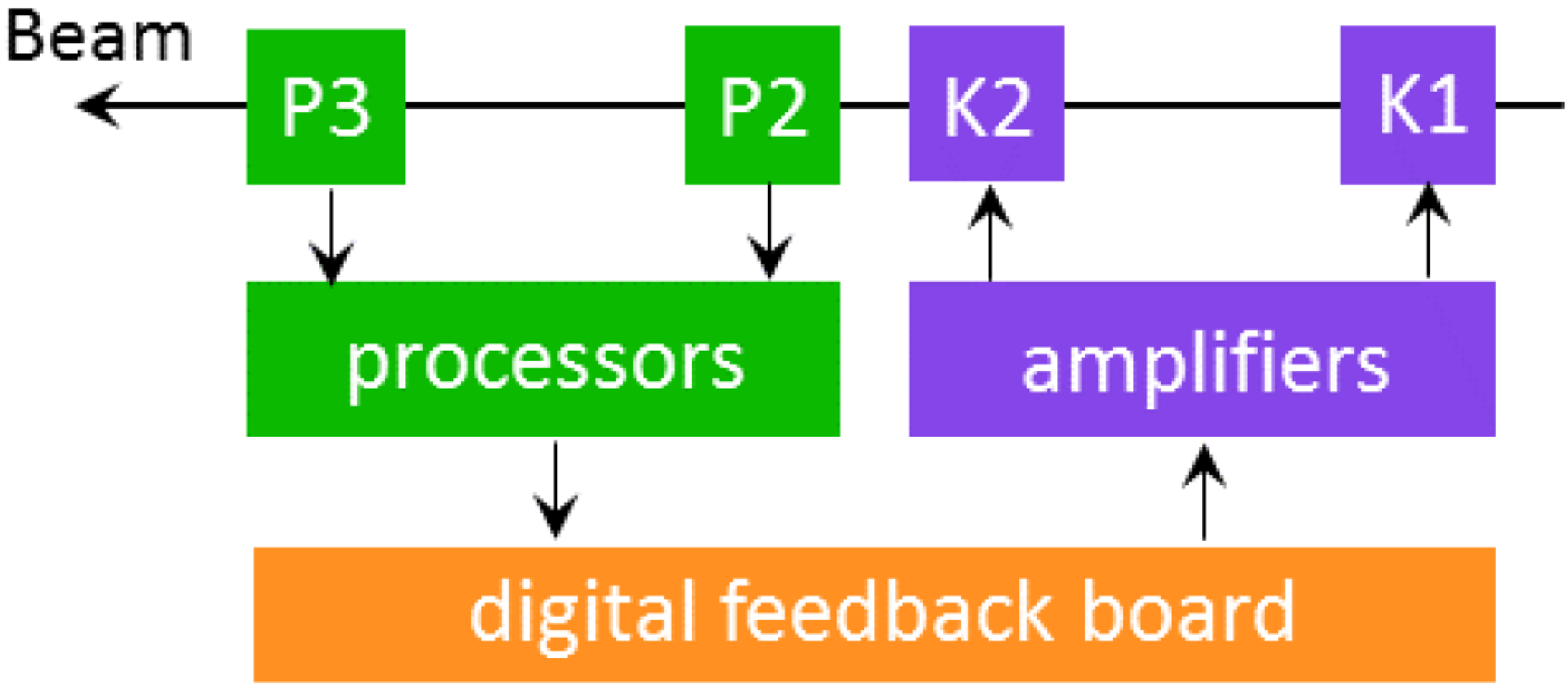
FONT5 installation at ATF2

IP FB system

Upstream dual-phase FB system



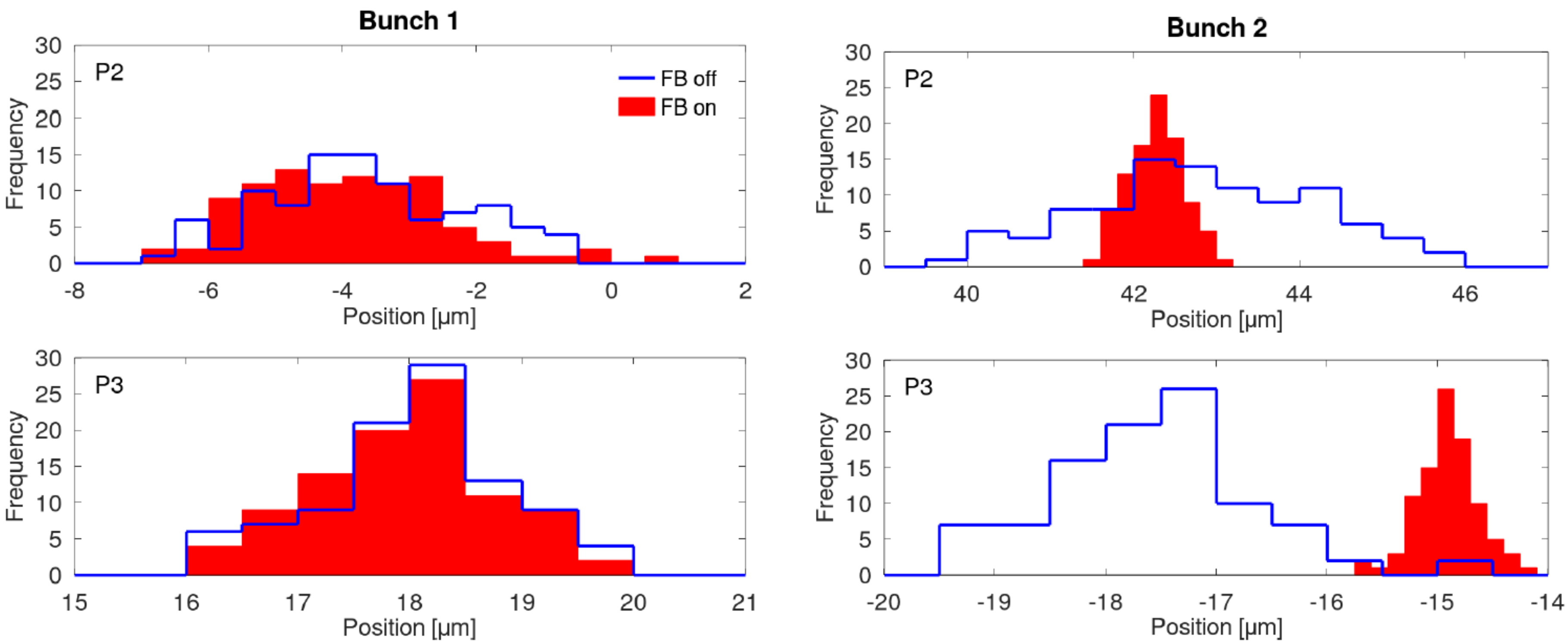
Upstream dual-phase FB system



Upstream dual-phase FB system

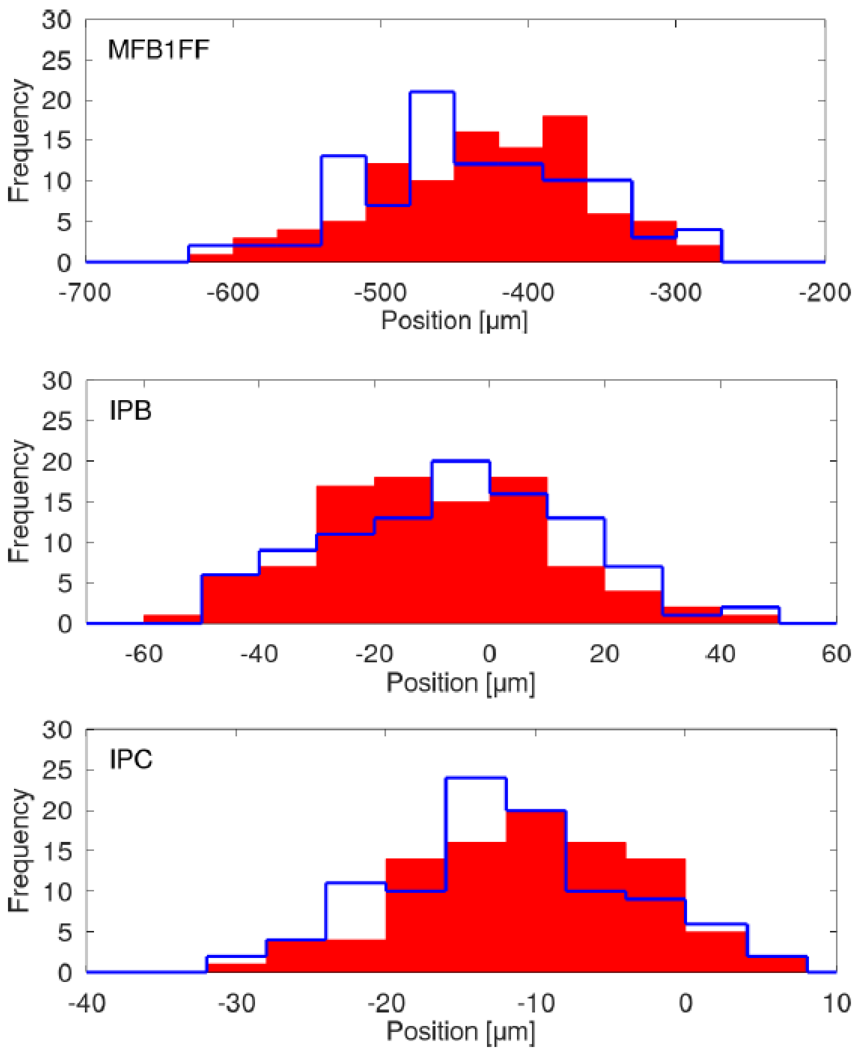
In-loop BPMs

Jitter reduced by factor ~4,
to BPM resolution (~200nm) limit

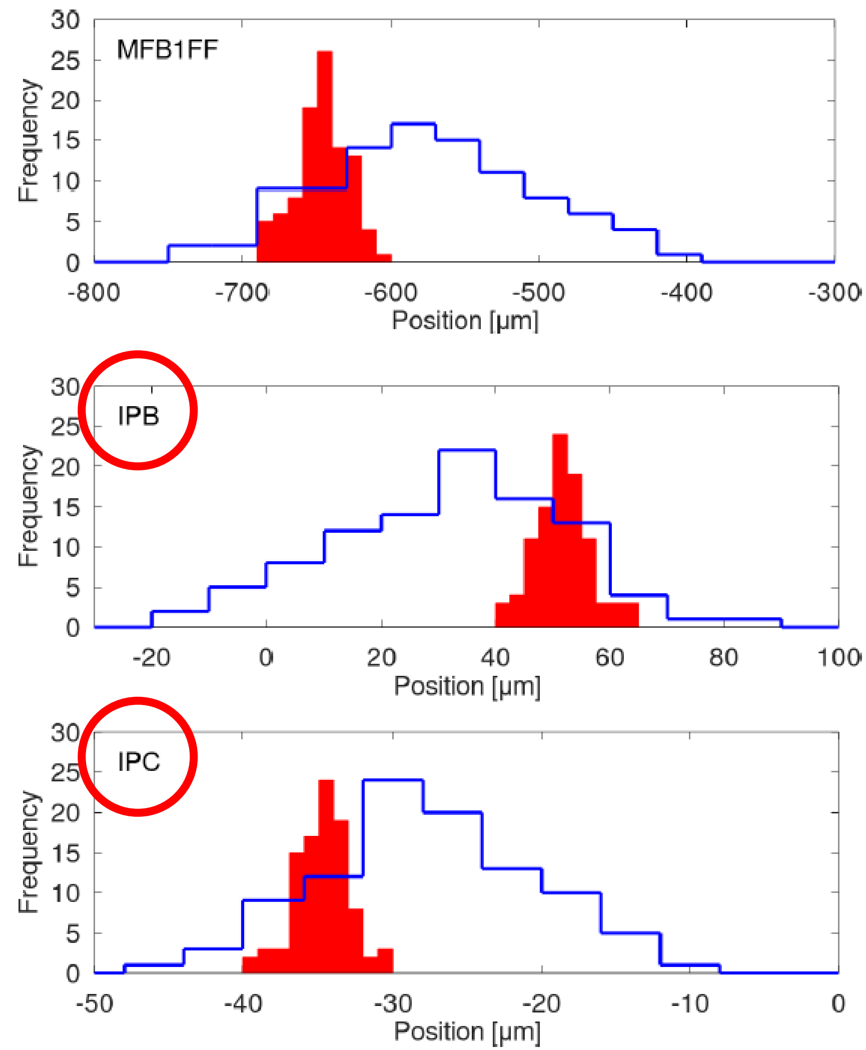


Upstream dual-phase FB system

Witness BPMs

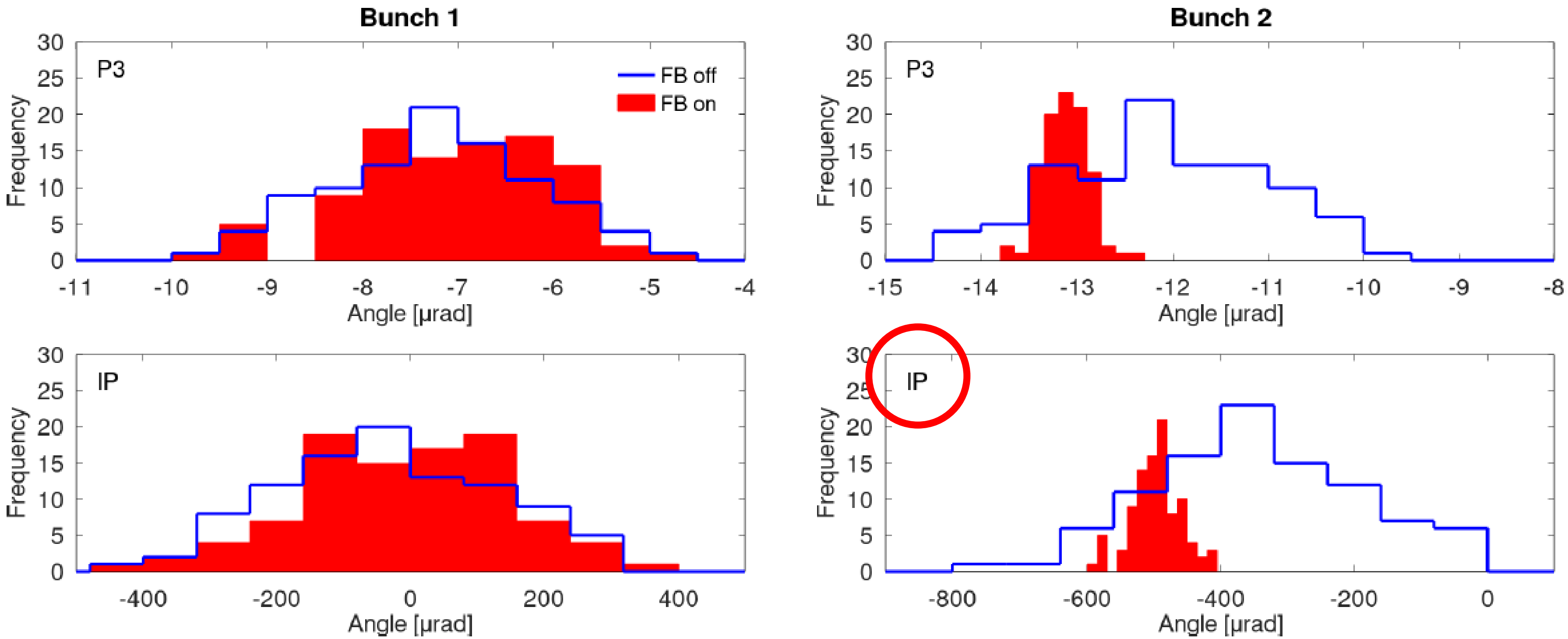


Jitter reduced by factor ~4 at IP



Upstream dual-phase FB system

Angle jitter reduced by factor ~4



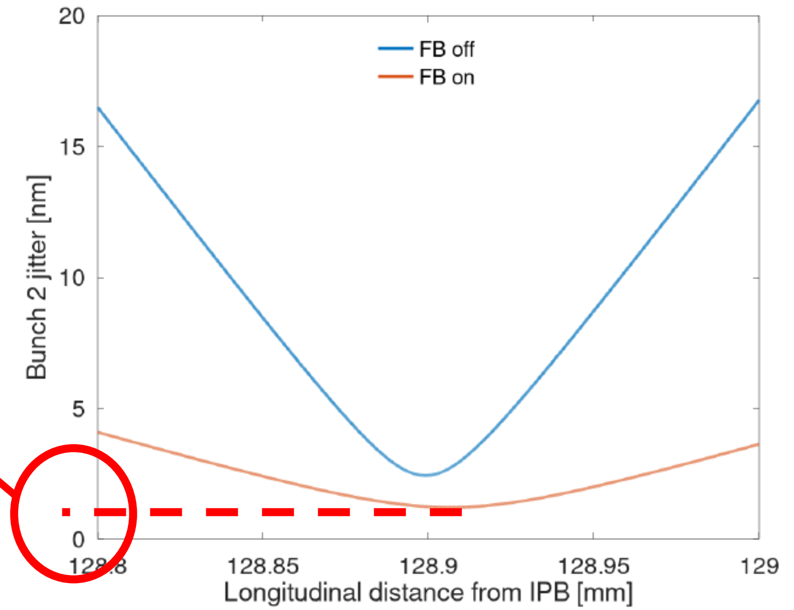
Upstream dual-phase FB system

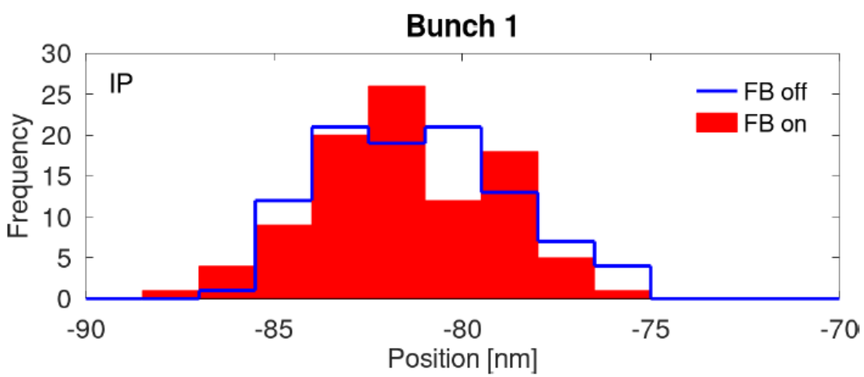
Track beam data from upstream region to IP using MADX model

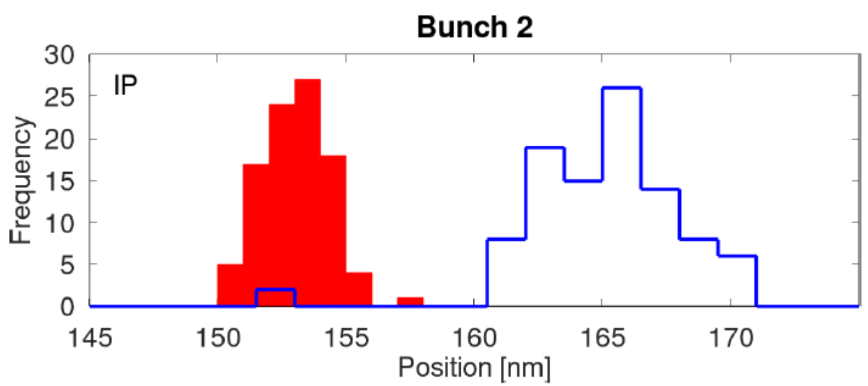
→ **beam stabilised to ~1nm at IP**

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

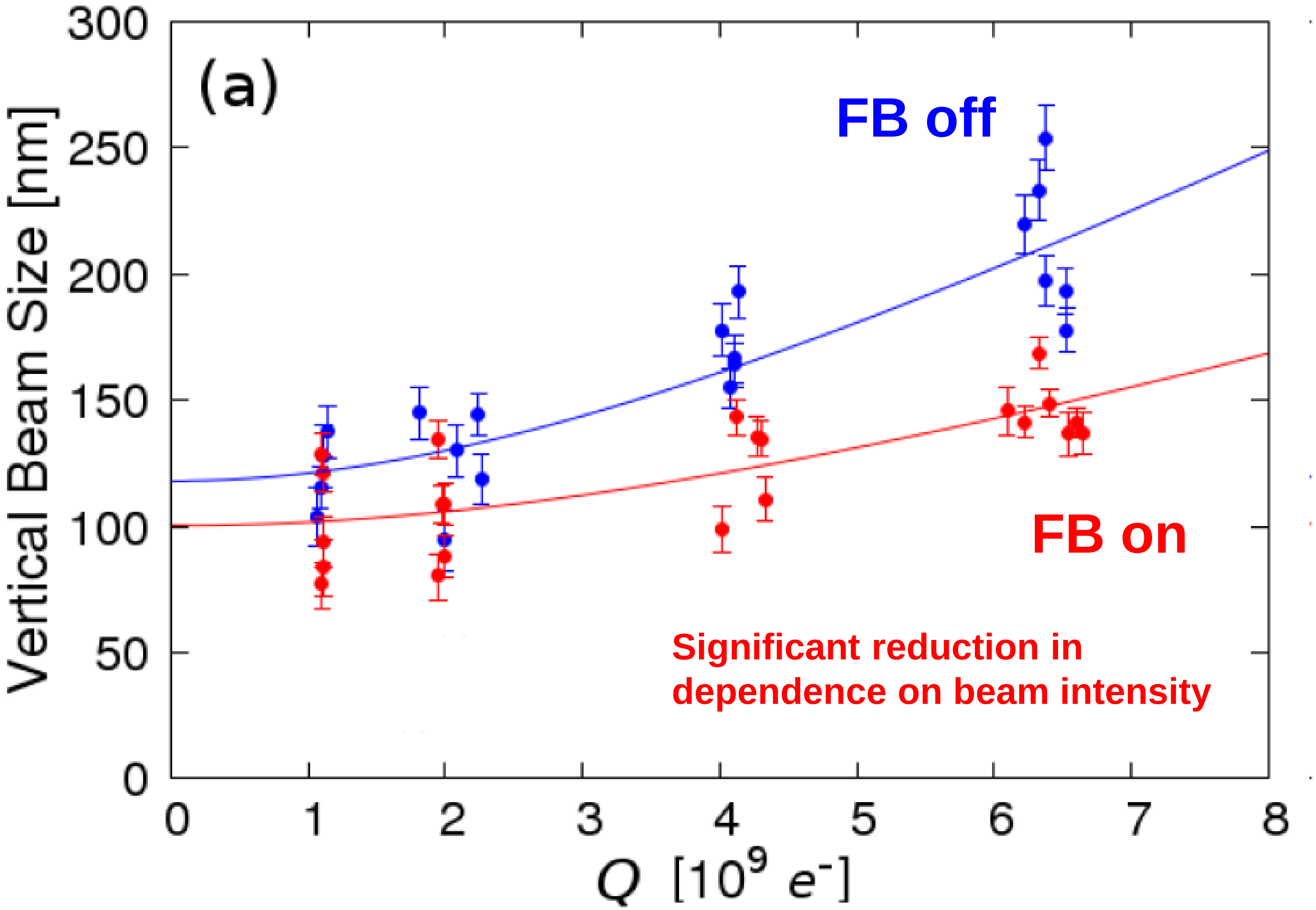
→ **not possible to measure directly with 1nm resolution!**







Upstream dual-phase FB system



Upstream dual-phase FB system

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

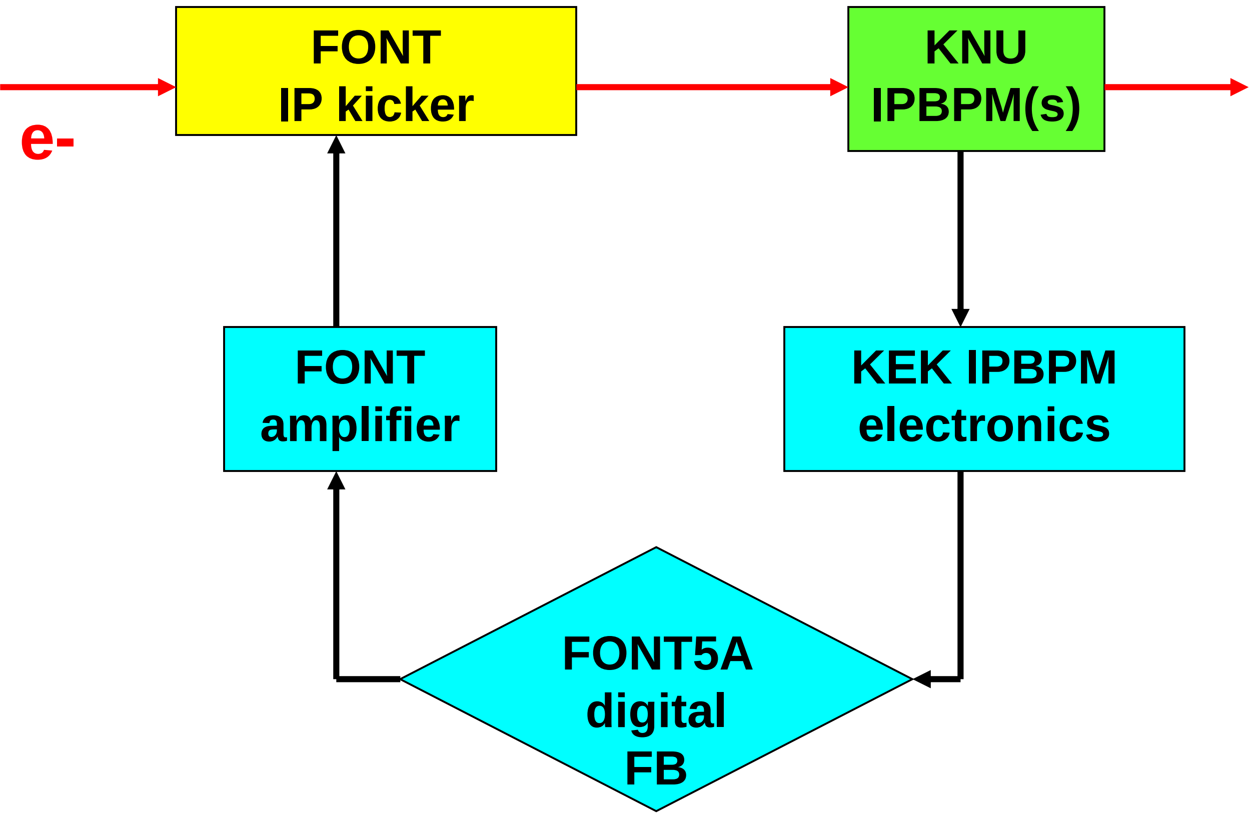
D. R. Bett,* P. N. Burrows, C. Perry, and R. Ramjiawan
John Adams Institute for Accelerator Science at University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom

N. Terunuma, K. Kubo, T. Okugi
High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Japan
(Dated: August 27, 2020)

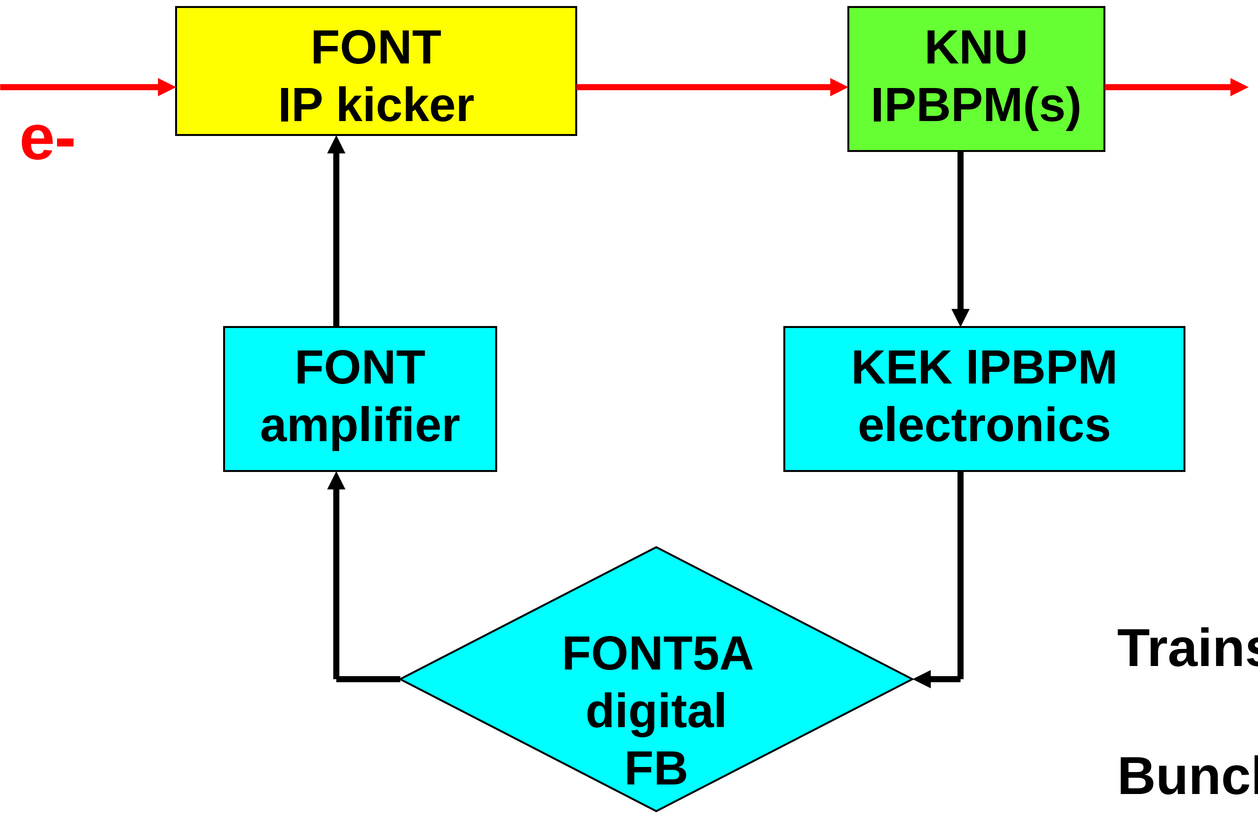
A high-precision intra-bunch-train beam orbit feedback correction system has been developed and tested in the ATF2 beamline of the Accelerator Test Facility at the High Energy Accelerator Research Organization in Japan. The system uses the vertical position of the bunch measured at two beam position 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.

arXiv:2008.12738 (2020)   submitted to J. Inst.

ATF2 ‘IP FB’ system



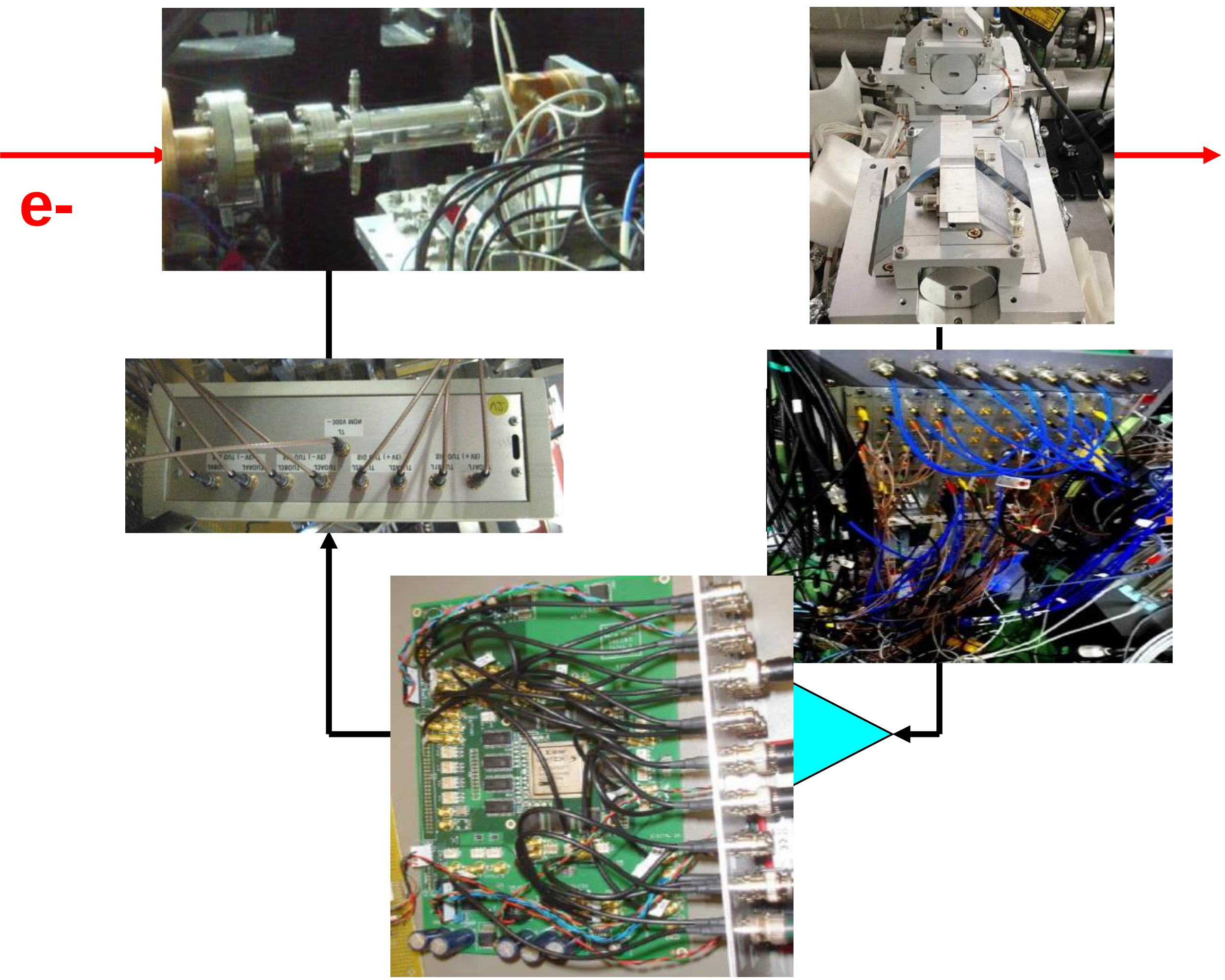
ATF2 'IP FB' system



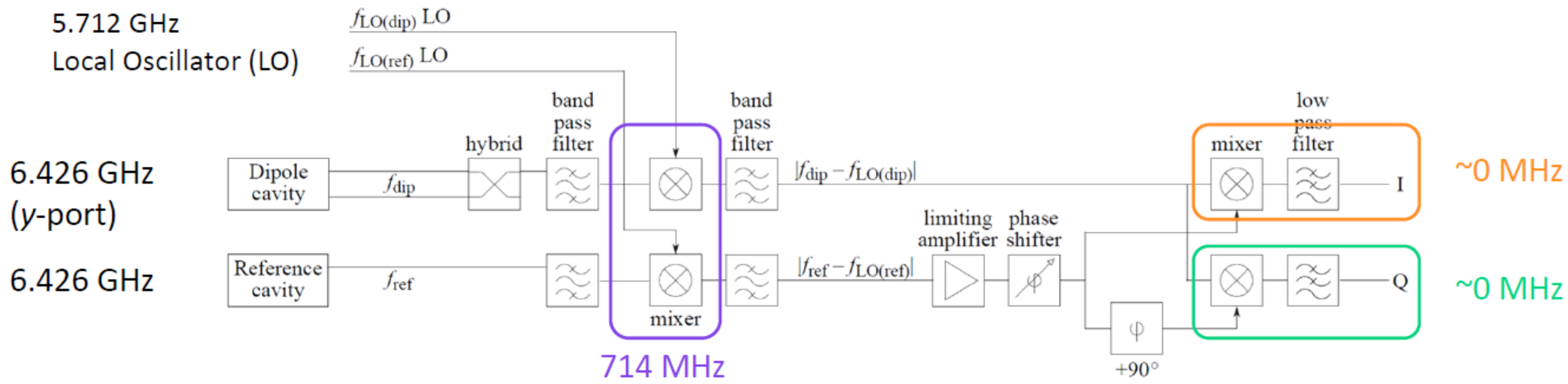
Trains of 2 bunches

Bunch separation c. 280 ns

ATF2 ‘IP FB’ system



BPM Signal Processing



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

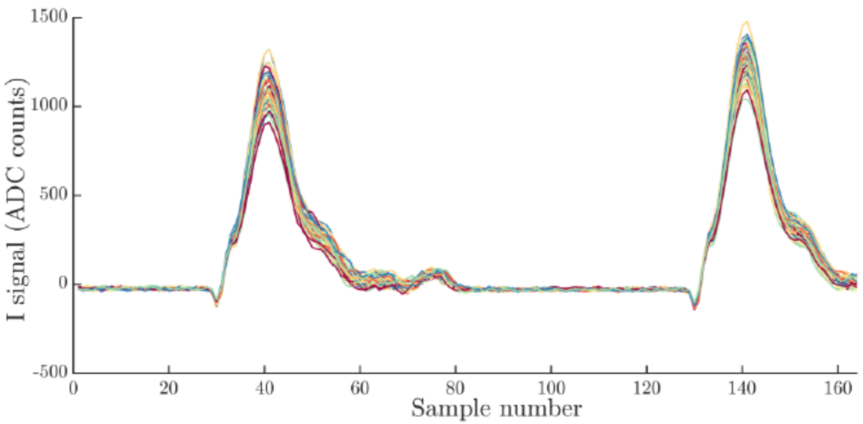
- The waveforms I and Q are digitised at 357 MHz by ADCs on the FONT 5A board; these digitised samples are used to compute a bunch position:

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

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.

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

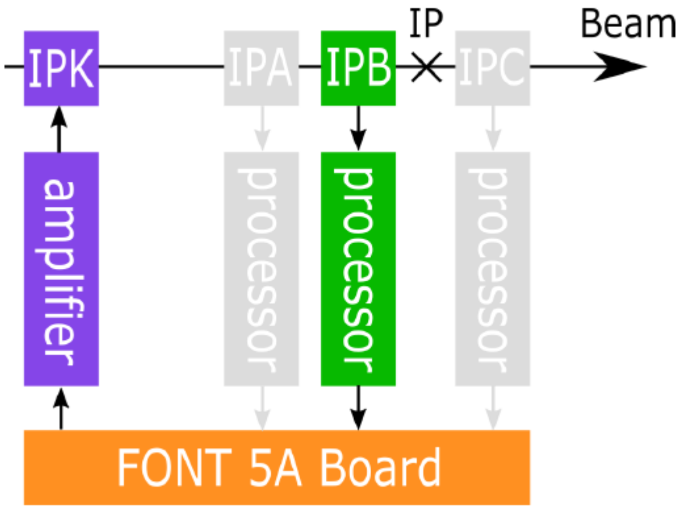
  FB loop latency measured ~ 232 ns

ATF2 ‘IP FB’ results

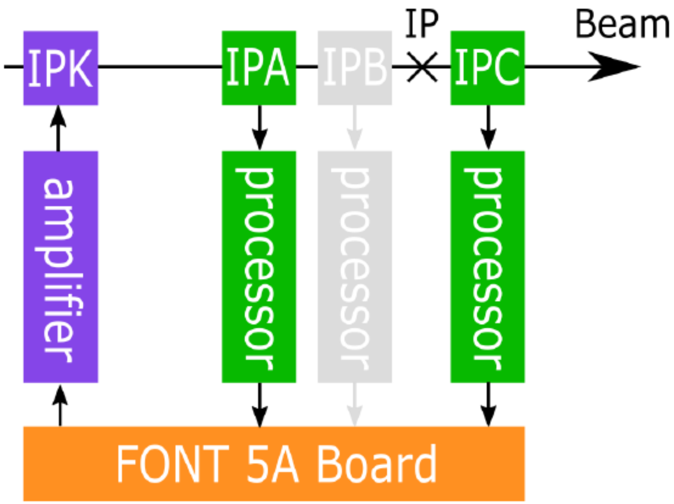
- Best real-time IPBPM resolution ~ 20 nm (< 25nm routine)

ATF2 'IP FB' results

- Best real-time IPBPM resolution ~ 20 nm (< 25nm routine)



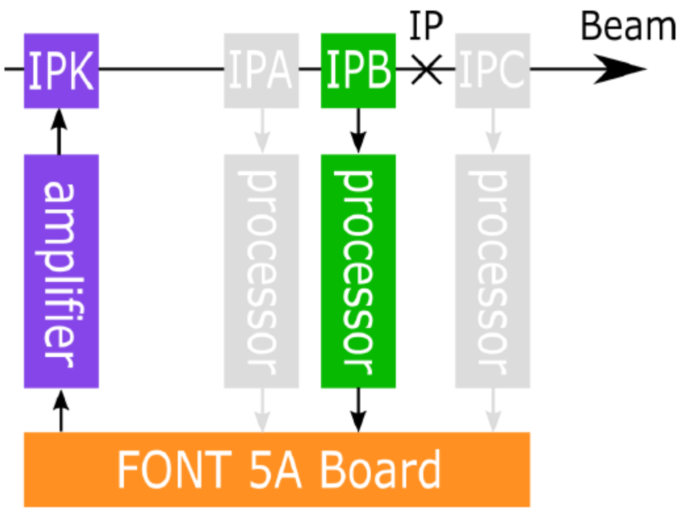
	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	109 ± 11	118 ± 8
2	119 ± 12	50 ± 4



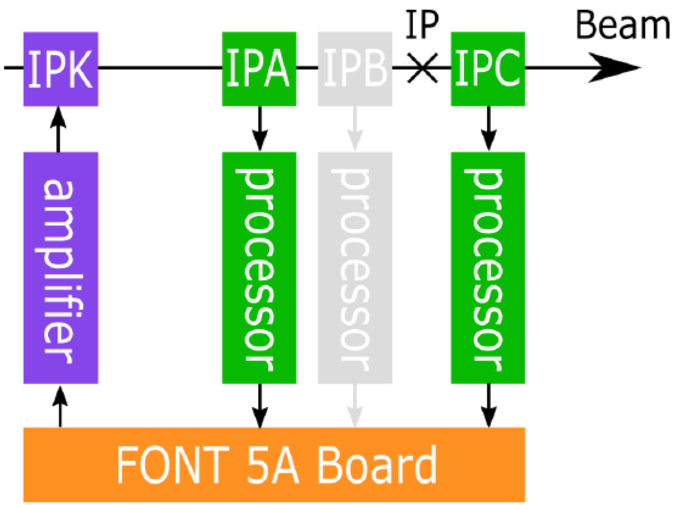
	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	106 ± 16	106 ± 16
2	96 ± 10	41 ± 4

ATF2 ‘IP FB’ results

- **Best real-time IPBPM resolution ~ 20 nm (< 25nm routine)**



	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	109 ± 11	[illegible]
2	119 ± 12	50 ± 4



	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	106 ± 16	[illegible]
2	96 ± 10	41 ± 4

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

Summary + outlook

- ILC IP FB system prototyped + tested:
  meets ILC performance specifications
- Upstream dual-phase FB provides capability for
  1 nm-level beam stabilisation at ATF2 IP
- ATF2 'IP FB' has stabilised beam directly locally
  to c. 40 nm; 25 nm is possible in principle
- Upstream FB reduced observed intensity-dependence of beam size by factor ~ 1.6
- Additional beam time would allow:
  optimisation of FB system performance
  study of long-term beam trajectory control

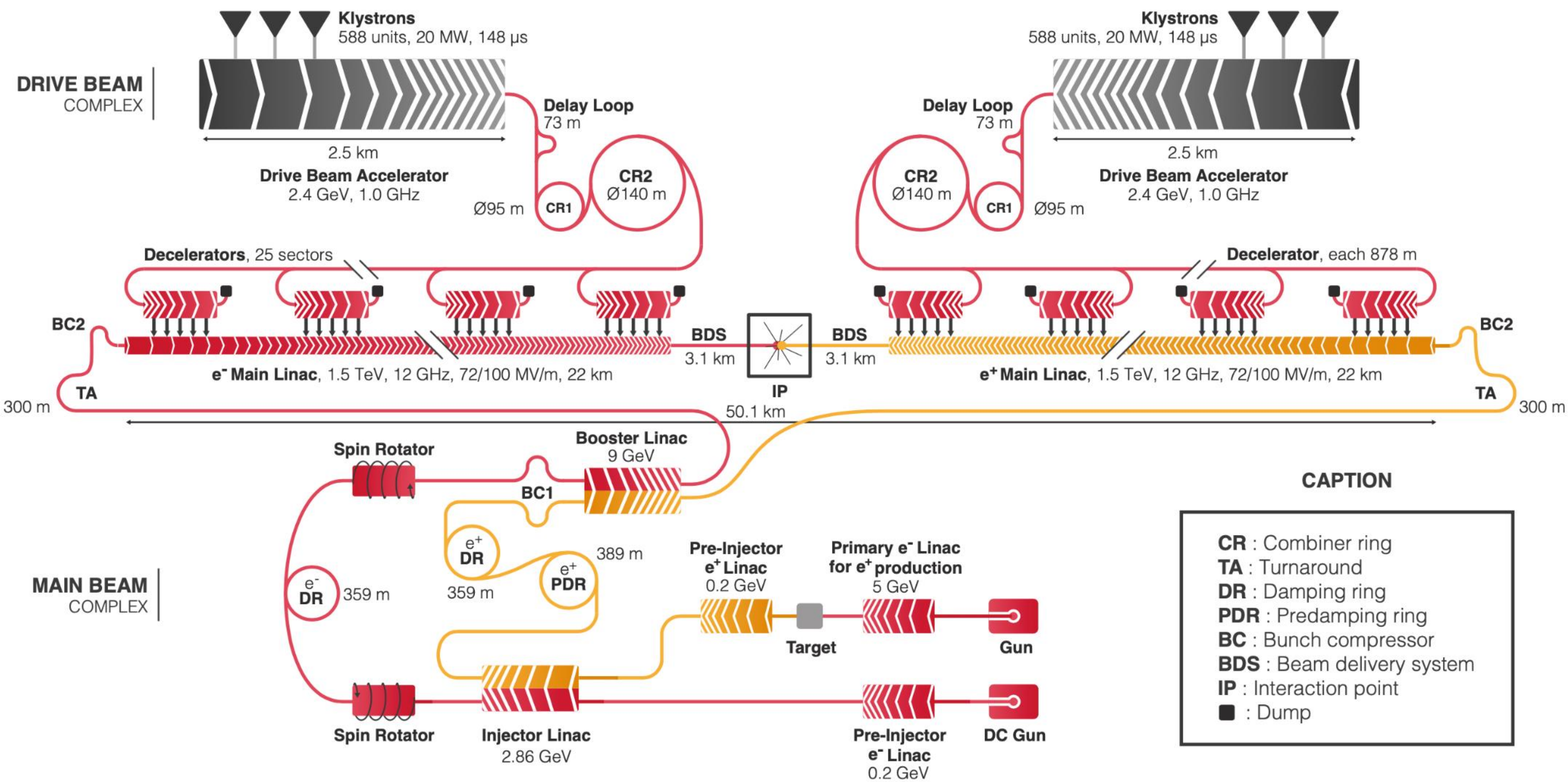
Extra material

Beam parameters

	ILC 250	500	
Electrons/bunch	2	2	10**10
Bunches/train	1312	1312	
Bunch separation	554	544	ns
Train length	727	727	us
Train repetition rate	5	5	Hz
Horizontal IP beam size	516	474	nm
Vertical IP beam size	8	6	nm
Luminosity	1.4	1.8	10**34

Compact Linear Collider

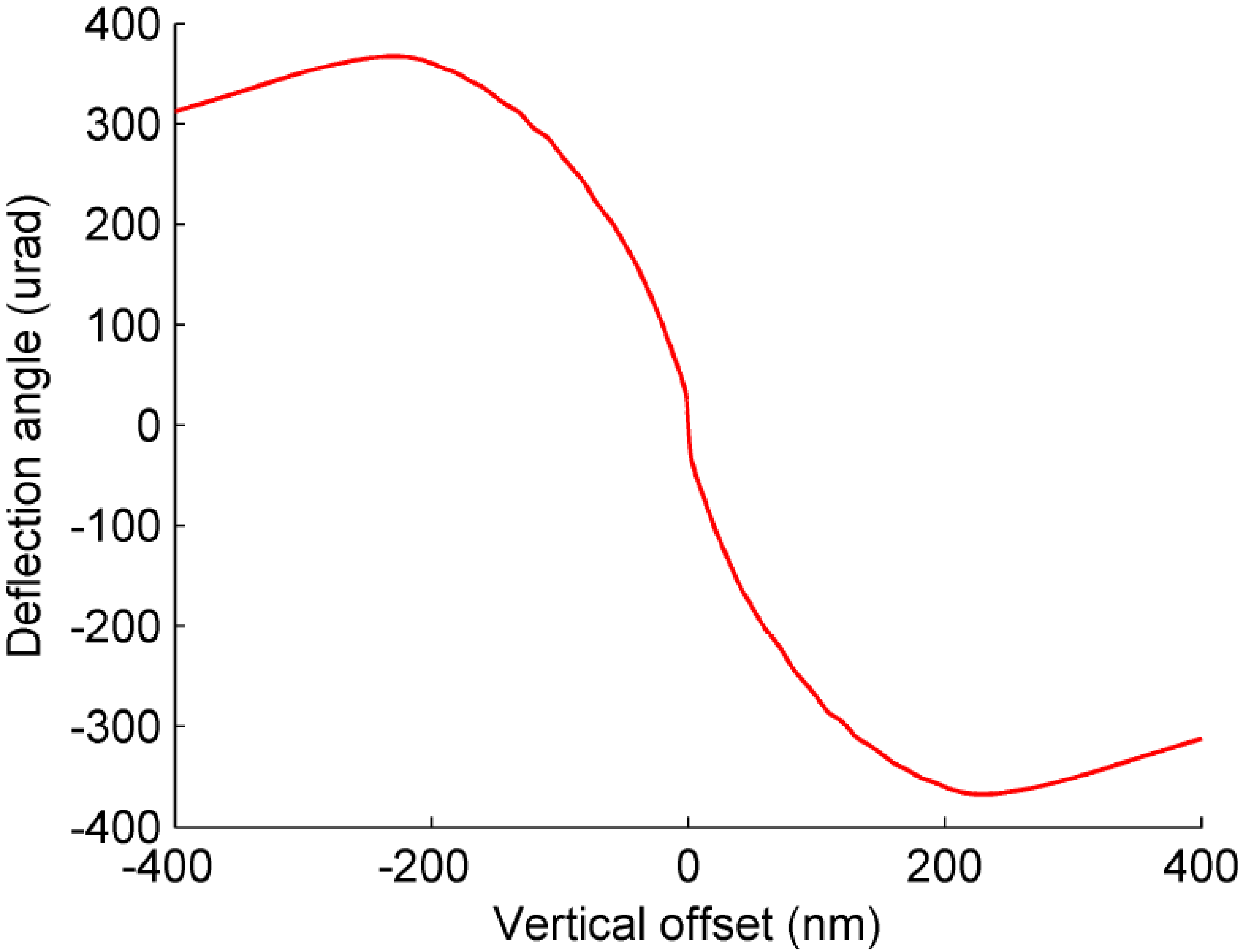
3 TeV layout



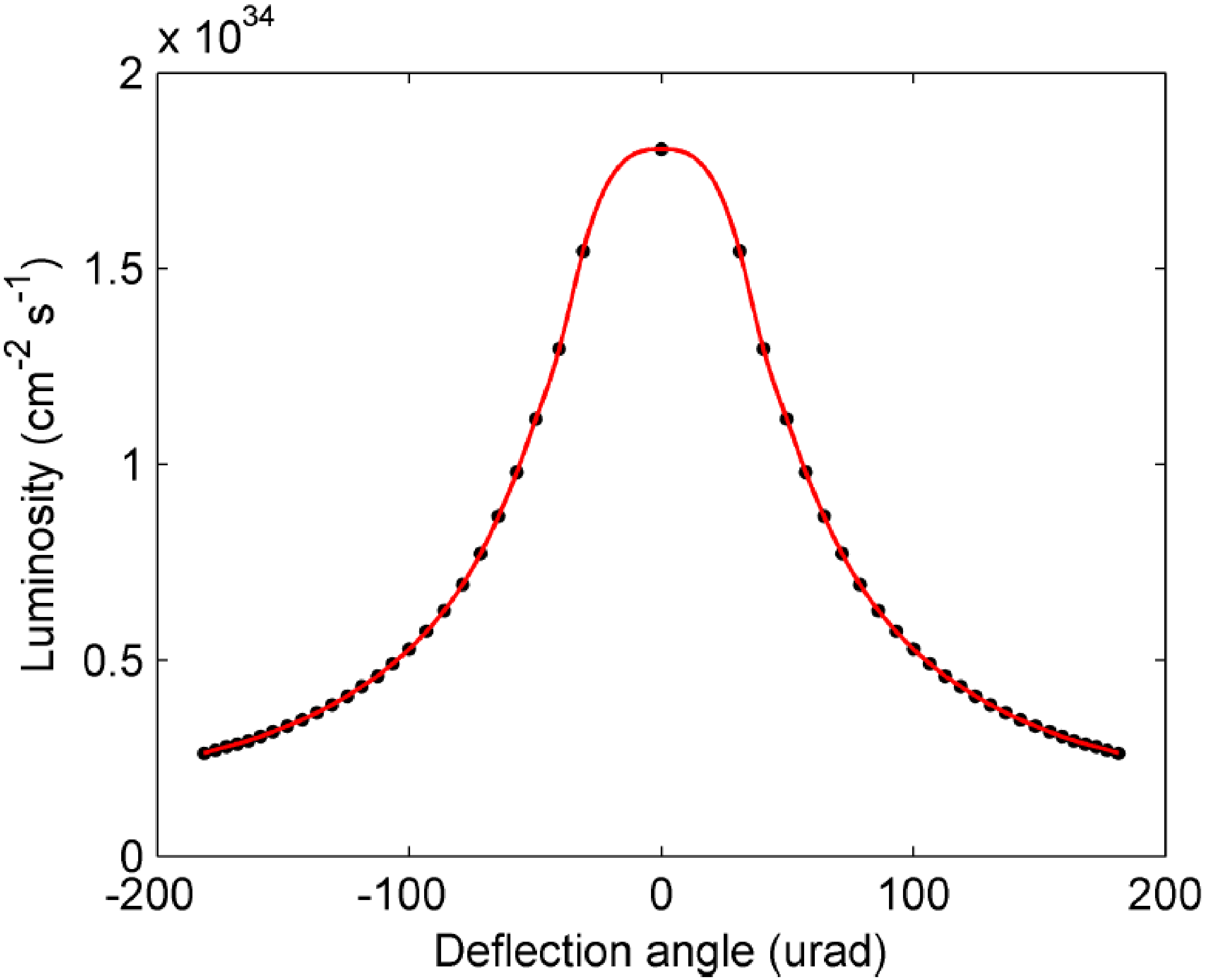
Beam parameters

	ILC 250	500	CLIC 3 TeV	
Electrons/bunch	2	2	0.37	10**10
Bunches/train	1312	1312	312	
Bunch separation	554	544	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

Beam-beam deflection (ILC500)



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 (500 GeV): c. 1300 bunches w. c. 500 ns separation

CLIC (3 TeV): 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:

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

IP FB Design Status: CLIC

Conceptual design developed and documented in CLIC CDR (2012)

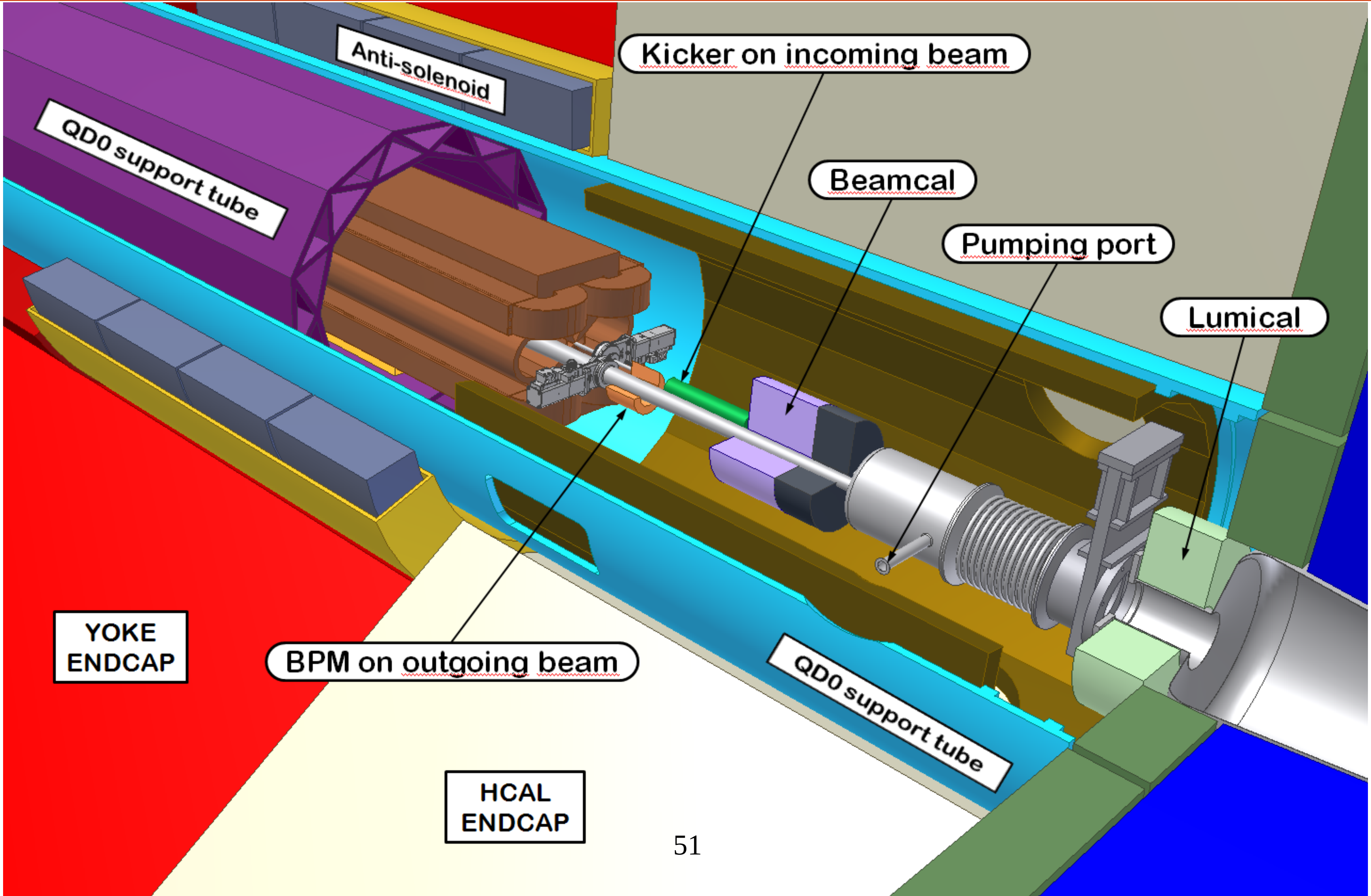
NB primary method for control of beam collision overlap is via vibration isolation of the FF magnets, and dynamic correction of residual component motions

IP position feedback:

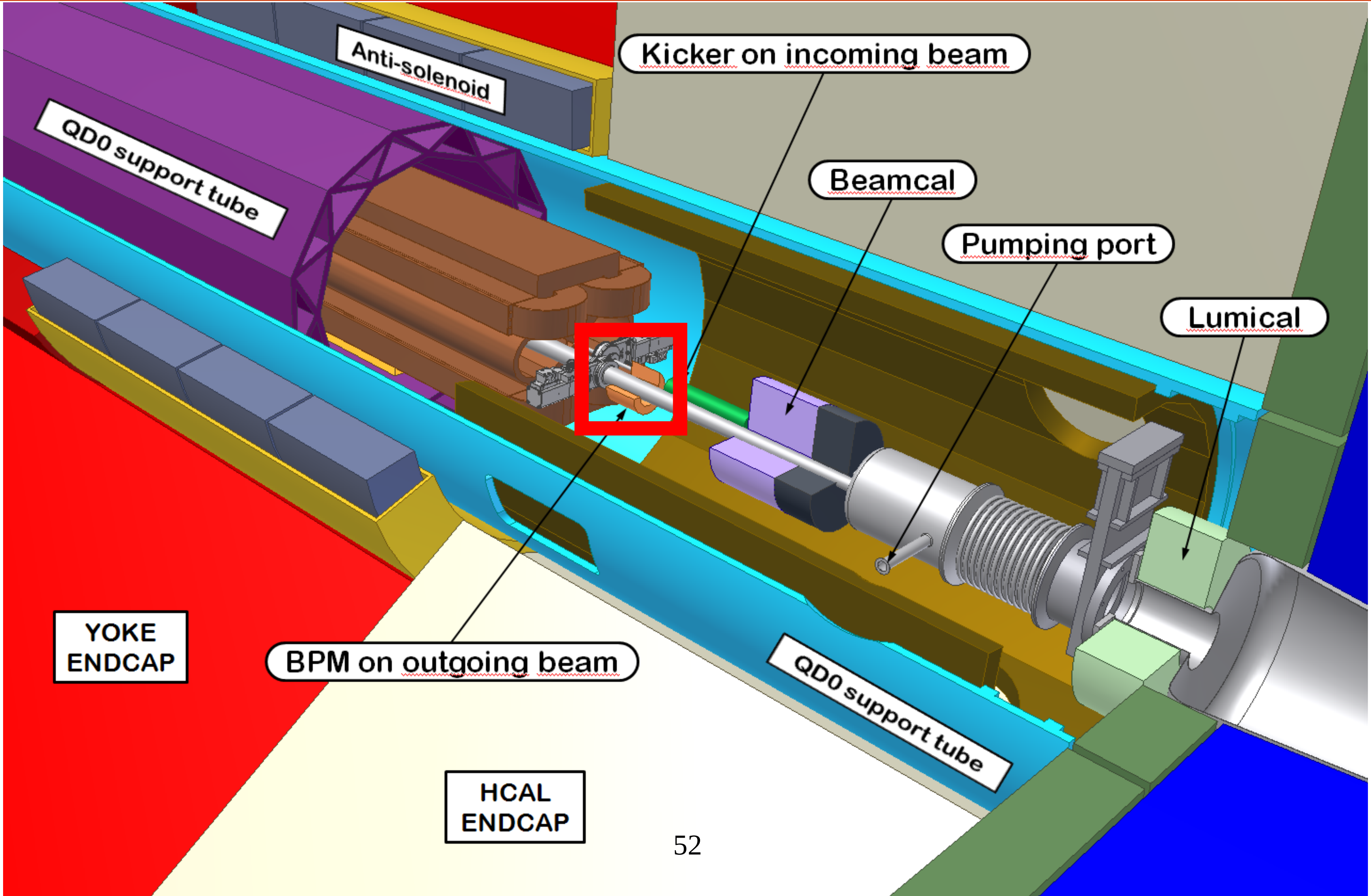
beam position correction up to +- 50 nm vertical at IP

More realistic engineering design in development

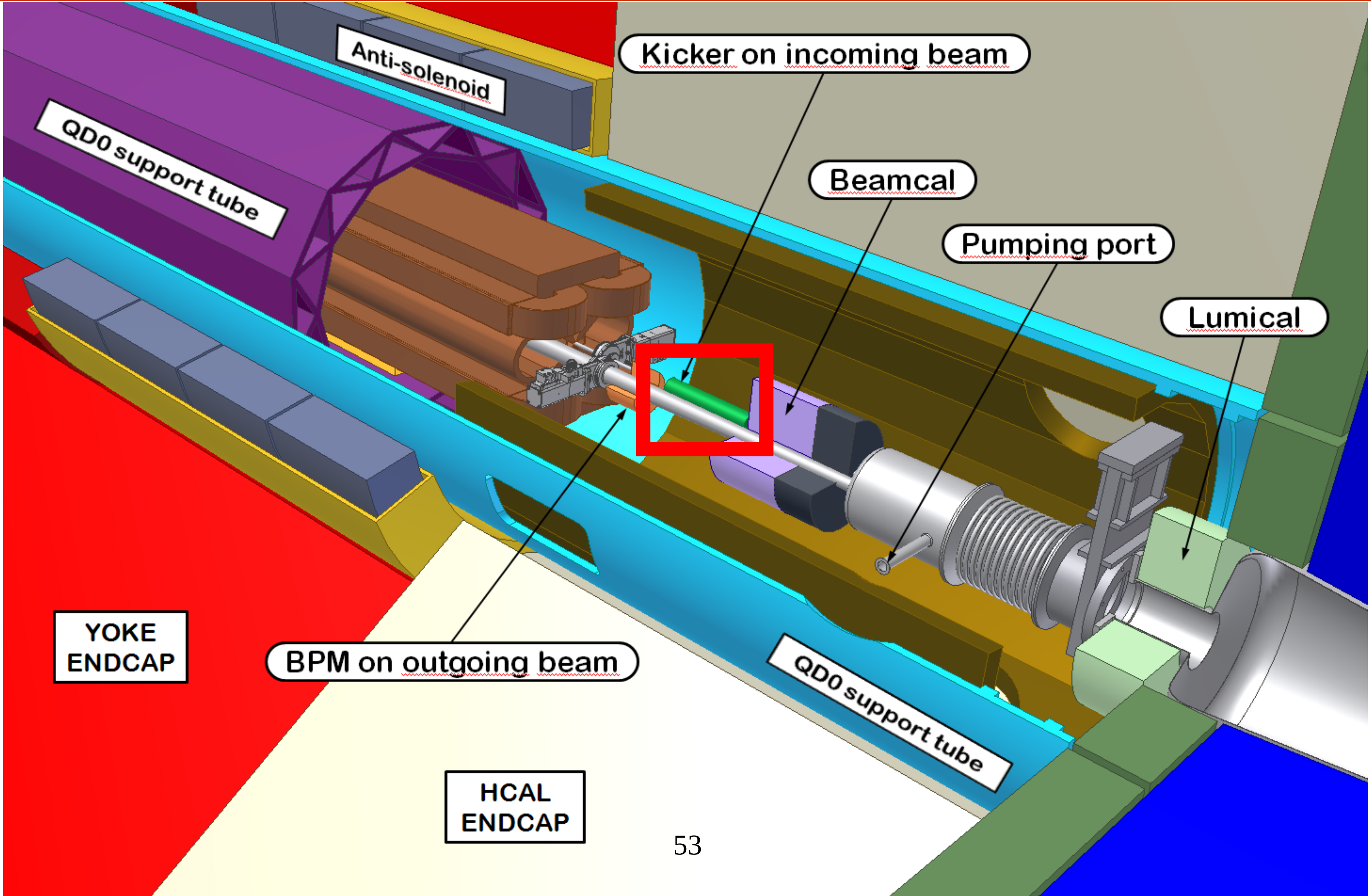
CLIC Final Doublet Region



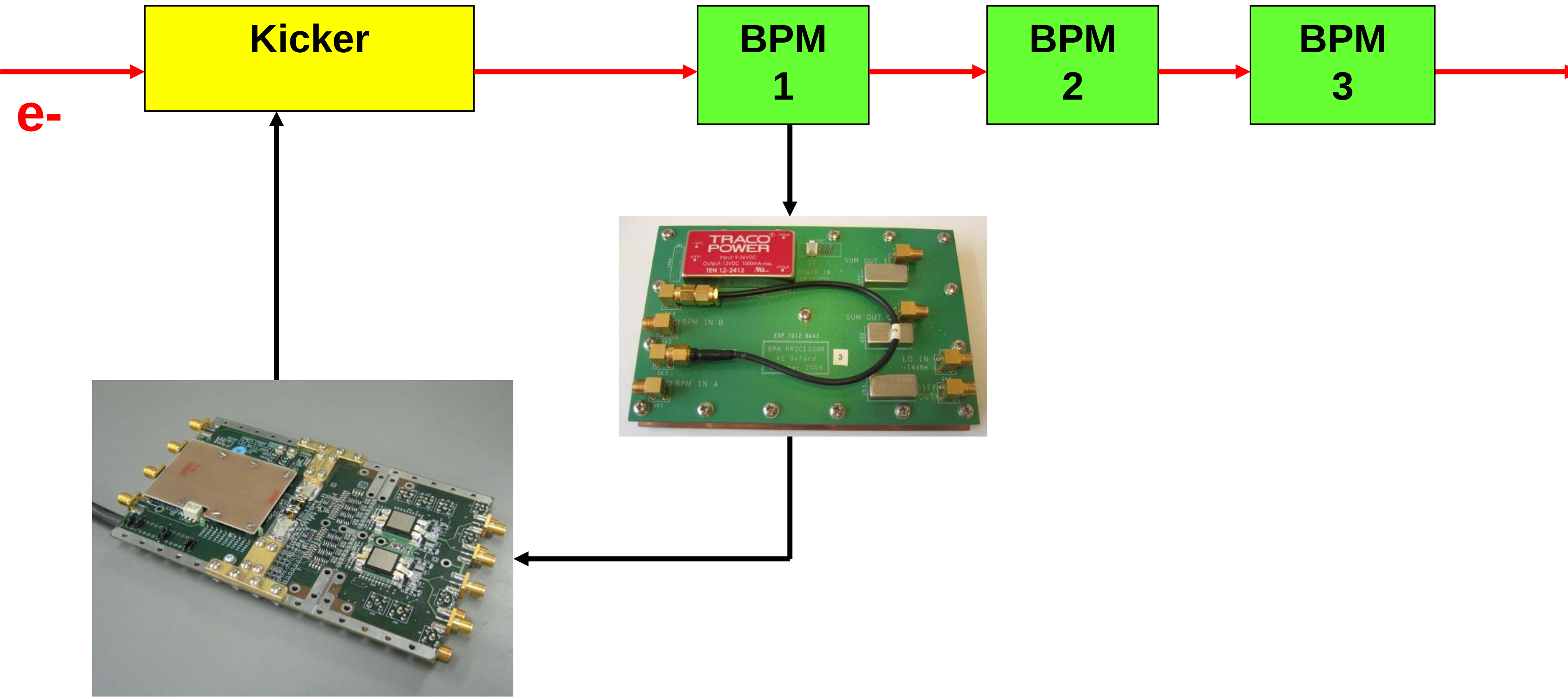
CLIC Final Doublet Region



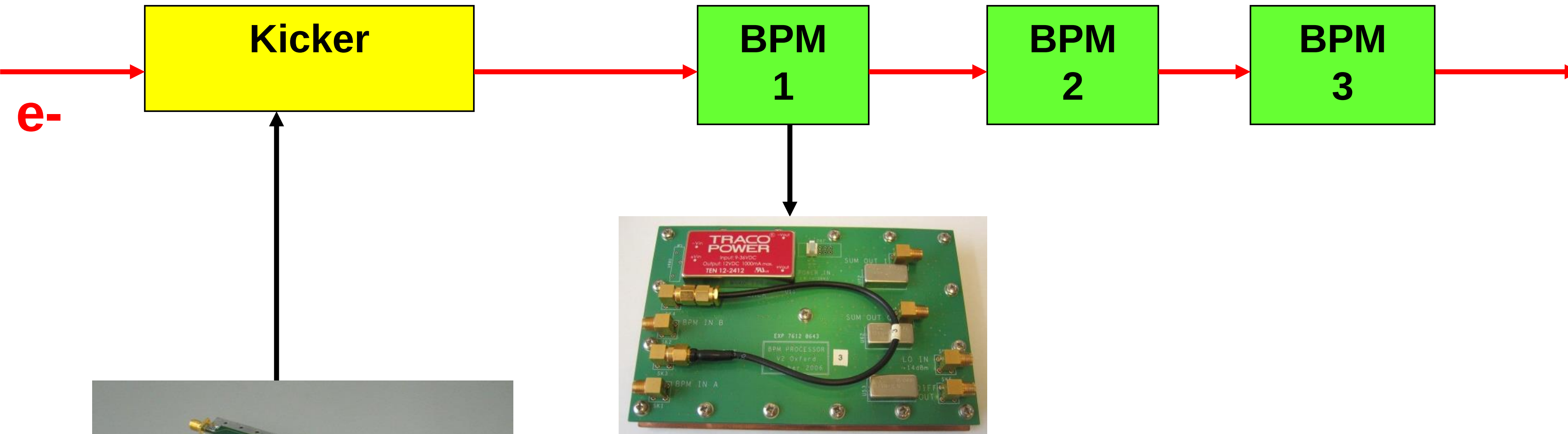
CLIC Final Doublet Region

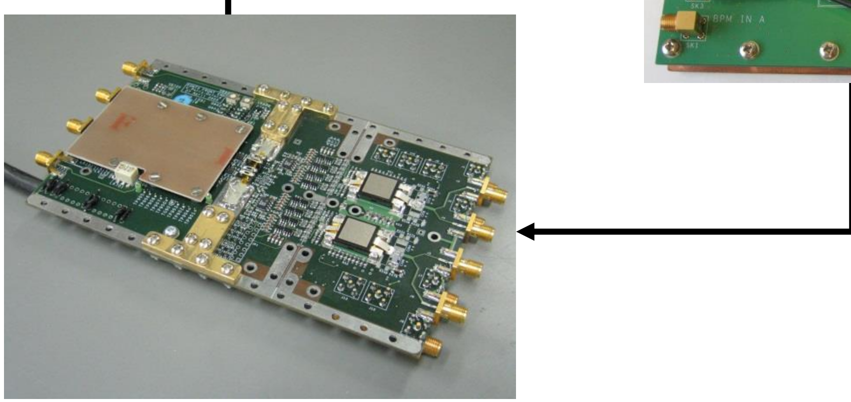


CLIC prototype: FONT3 at KEK/ATF



CLIC prototype: FONT3 at KEK/ATF



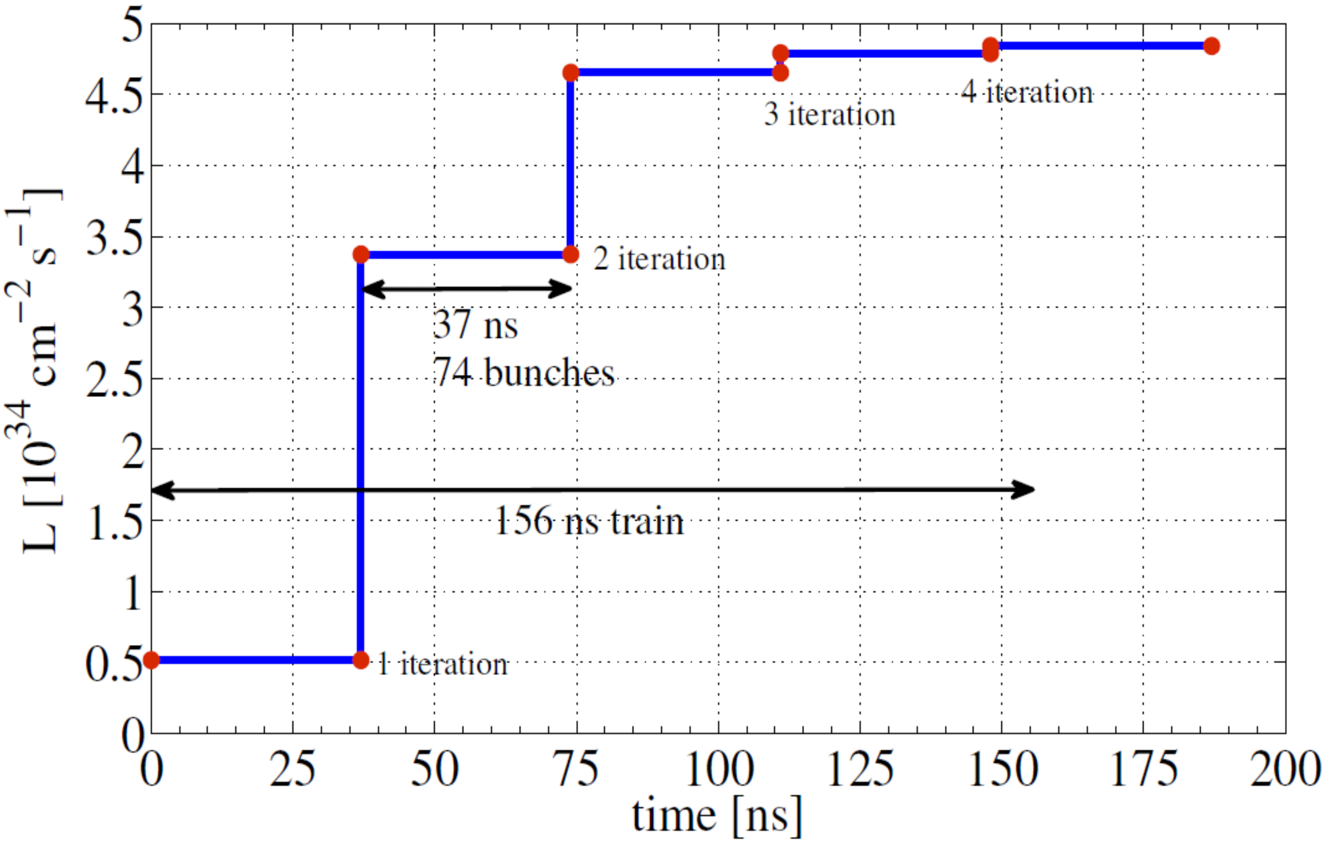


Electronics latency ~ 13ns

Drive power > 50nm @ CLIC

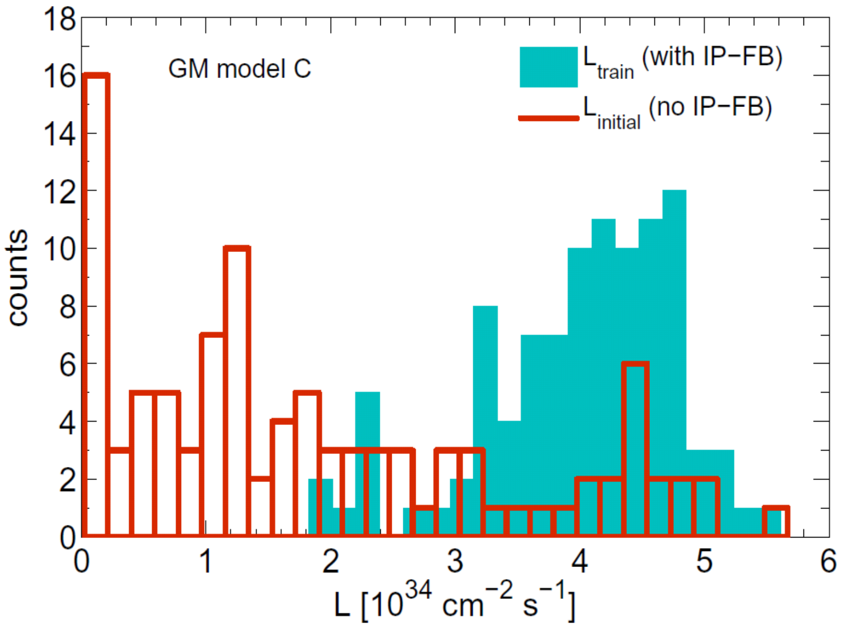
CLIC IP FB performance

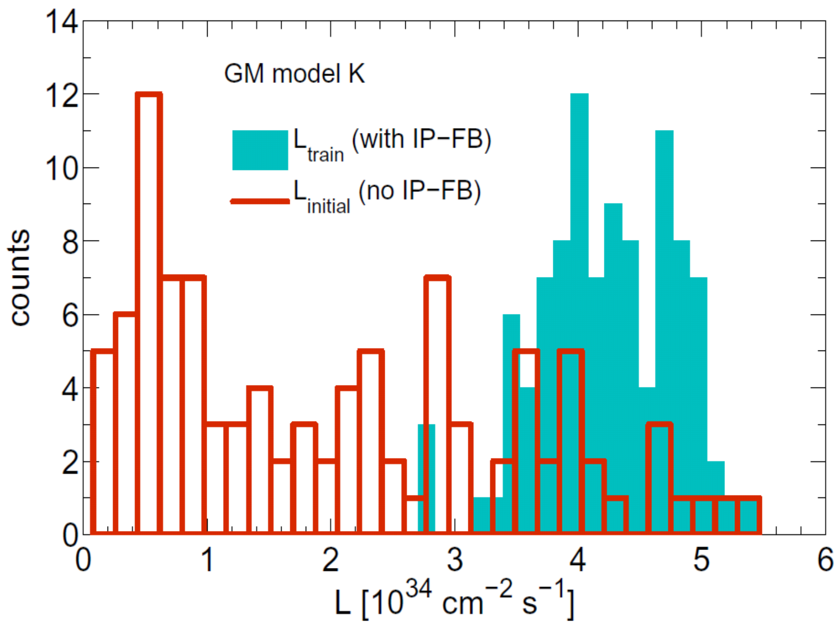
Single random seed of GM C



CLIC IP FB performance

For noisy sites:





→ **factor 2 - 3 improvement**

CLIC IP FB simulation paper

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

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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.

2010 JINST 5 P09007

Outstanding Engineering Issues

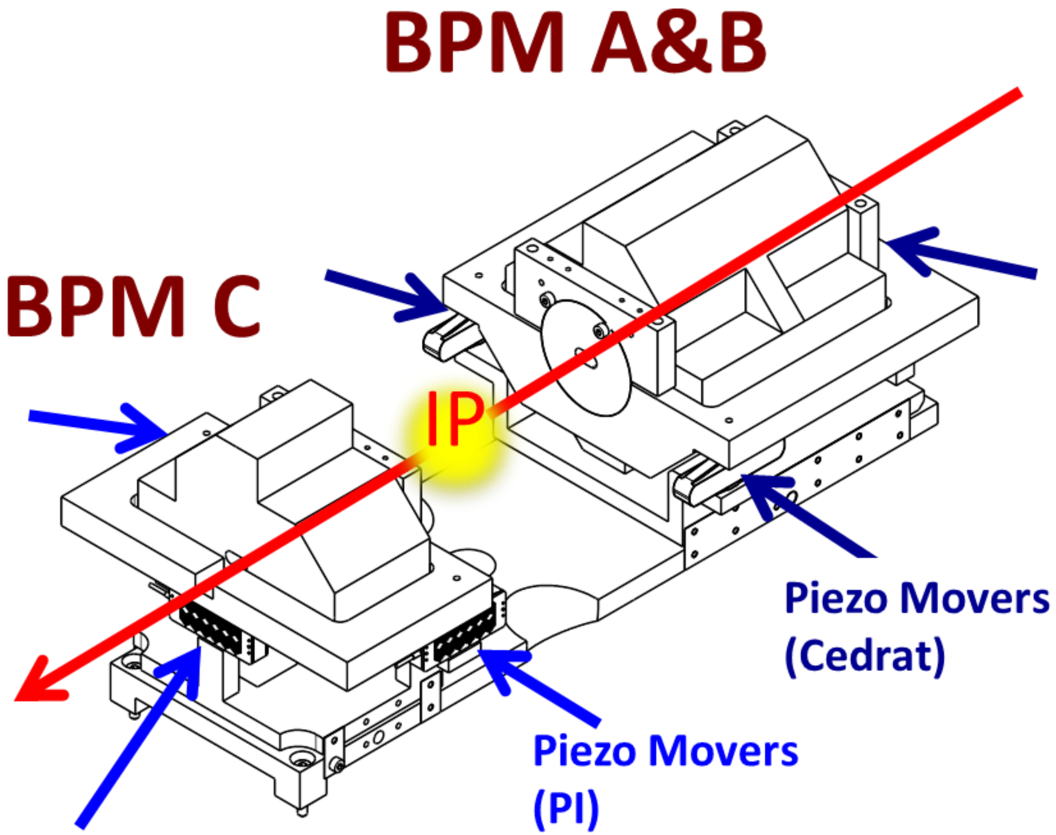
- Component designs need to be optimised for tight spatial environments
- Routing of cables
- Operation of (ferrite) devices in large, spatially-varying B-field
- Further studies of radiation environment
- Electronics location, rad hardness, shielding
- RF interference: beam ←→ FB electronics

  kicker ←→ detector

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**
- **Ideas applicable at XFELs + rings**

IP chamber including 3 cavity BPMs



JAI, KEK, KNU, LAL

3 cavity BPMs

Mover system for BPM alignment

Compact IP kicker