Progress on stabilising

relativistic lepton beams for future colliders

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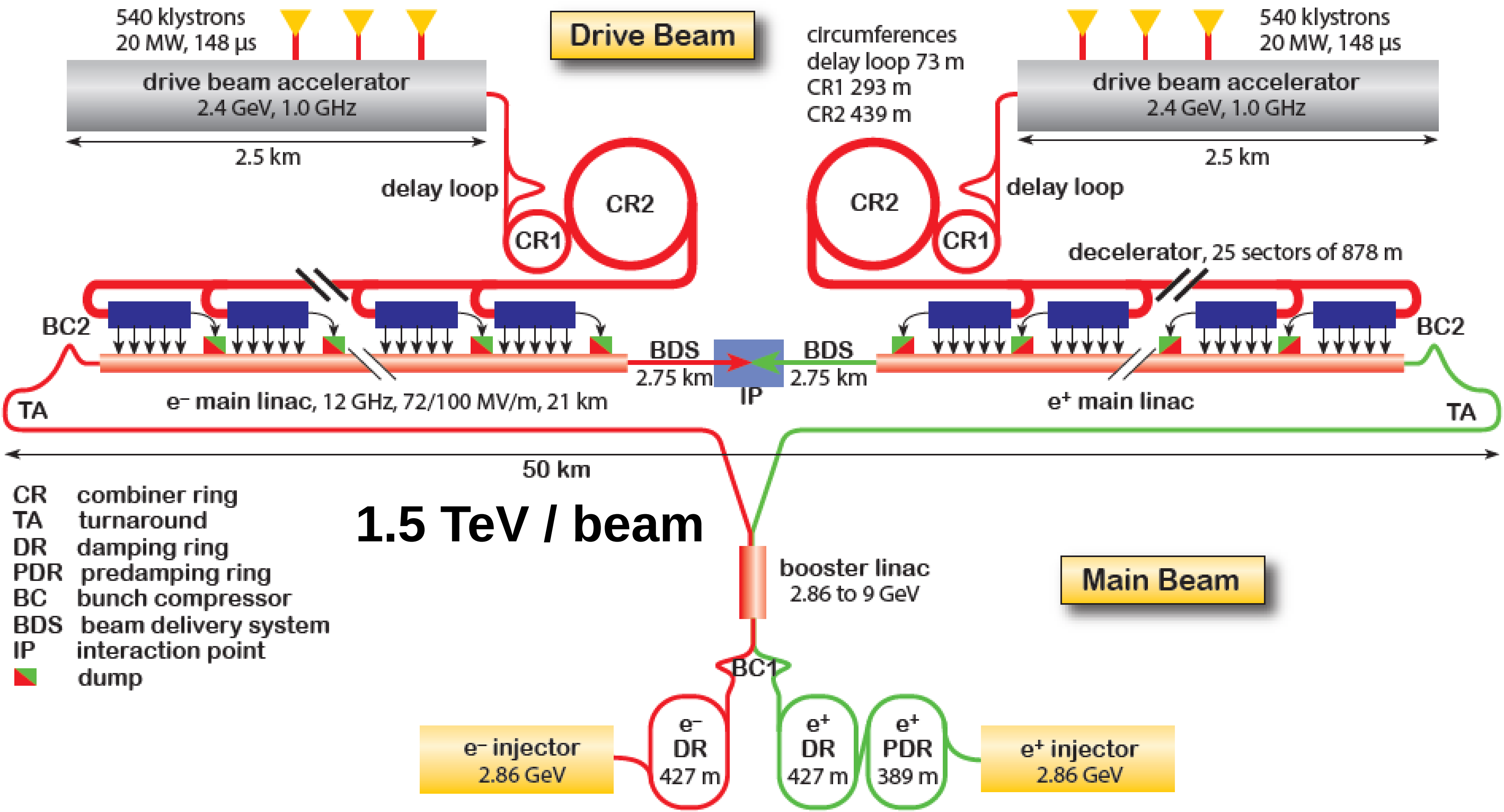
Outline

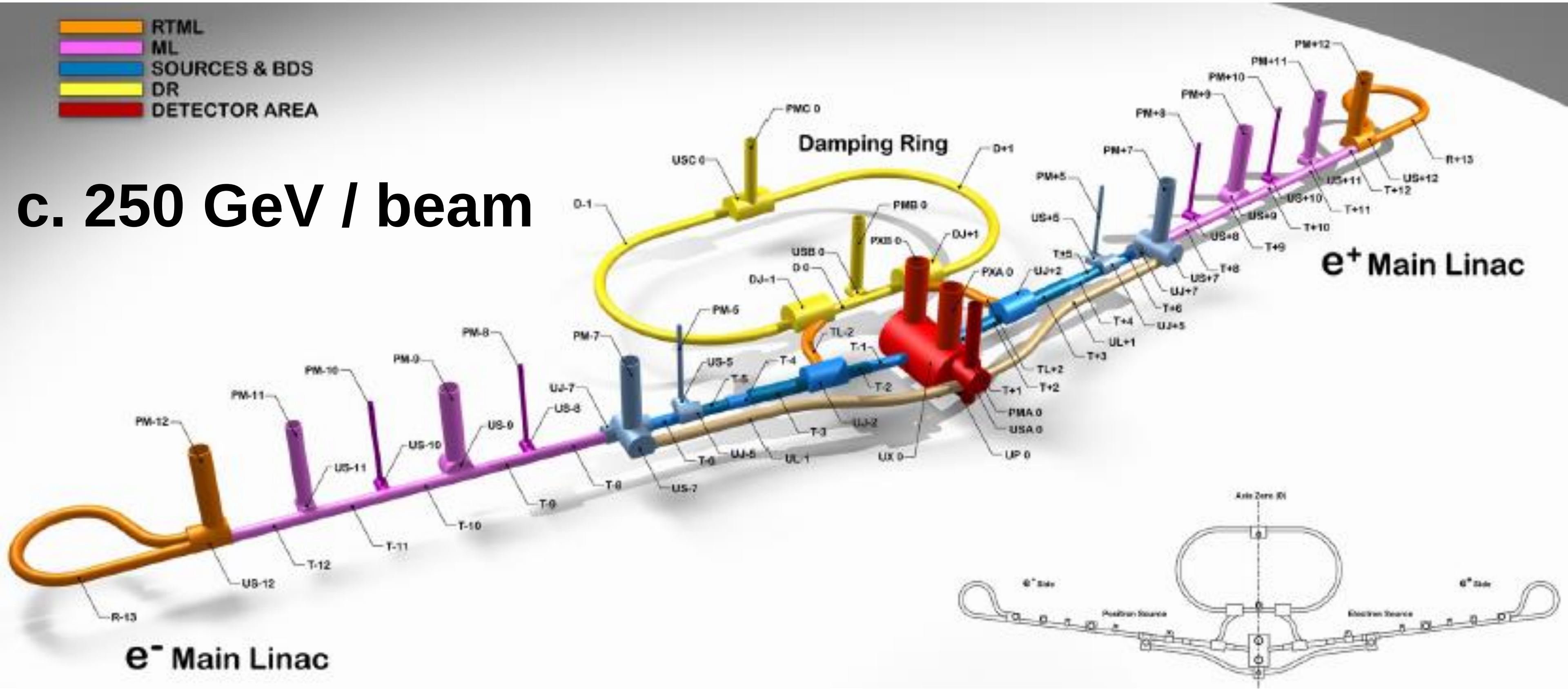
- Introduction and IP FB system concept
- ILC + CLIC IP FB design status
- FONT prototype systems performance
- Outstanding technical issues
- Latest beam stabilisation results from ATF2
- Summary

Compact Linear Collider (CLIC)



International Linear Collider

c. 250 GeV / beam



31 km

Beam parameters

ILC 250

Beam parameters

	ILC 250	
Electrons/bunch	2	10**10

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Bunches/train	1312	

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Horizontal IP beam size	729	nm
Vertical IP beam size	8	nm

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	729	nm
Vertical IP beam size	8	nm
Luminosity	0.8	10**34

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	4	Hz
Horizontal IP beam size	729	474	nm
Vertical IP beam size	8	6	nm
Luminosity	0.8	2	10**34

Beam parameters

	ILC 250	CLIC 3 TeV	
Electrons/bunch	2	0.37	10**10
Bunches/train	1312	312	
Bunch separation	554	0.5	ns
Train length	727	0.156	us
Train repetition rate	5	50	Hz
Horizontal IP beam size	729	40	nm
Vertical IP beam size	8	1	nm
Luminosity	0.8	6	10**34

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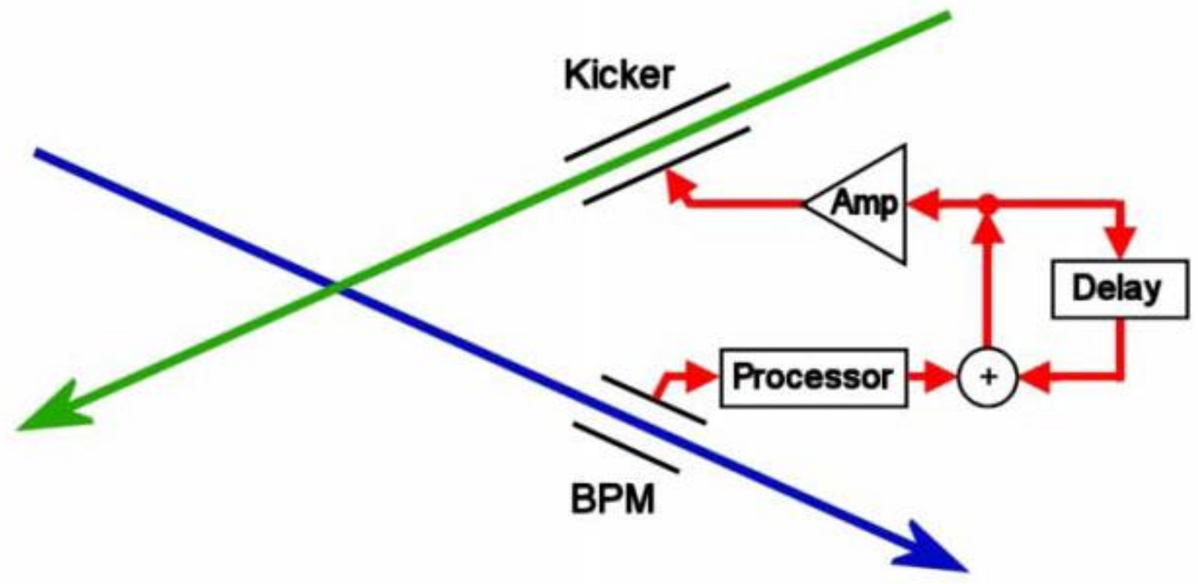
IP beam feedback concept

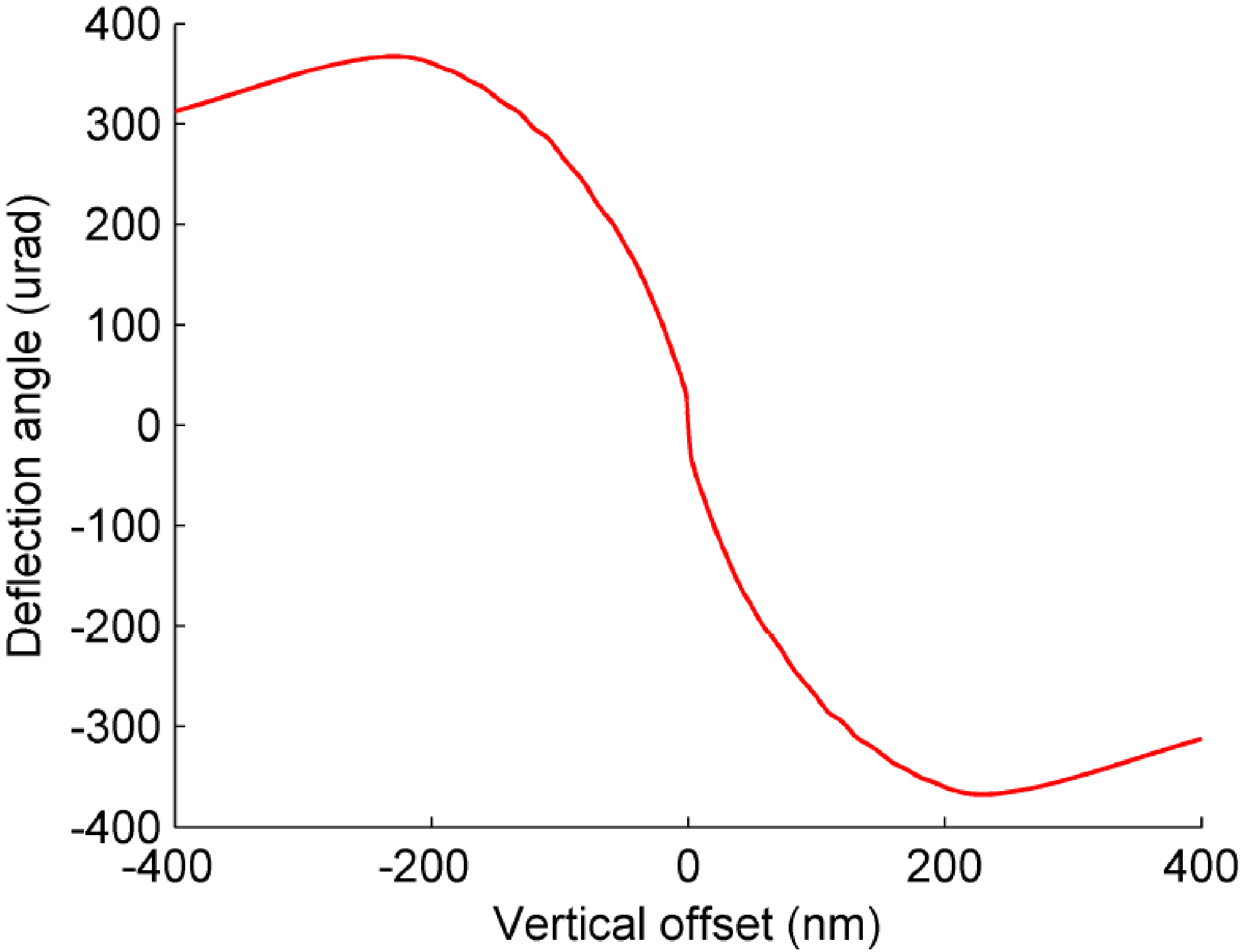
- Last line of defence against relative beam misalignment
- Measure vertical position of outgoing beam and hence beam-beam kick angle
- Use fast amplifier and kicker to correct vertical position of beam incoming to IR



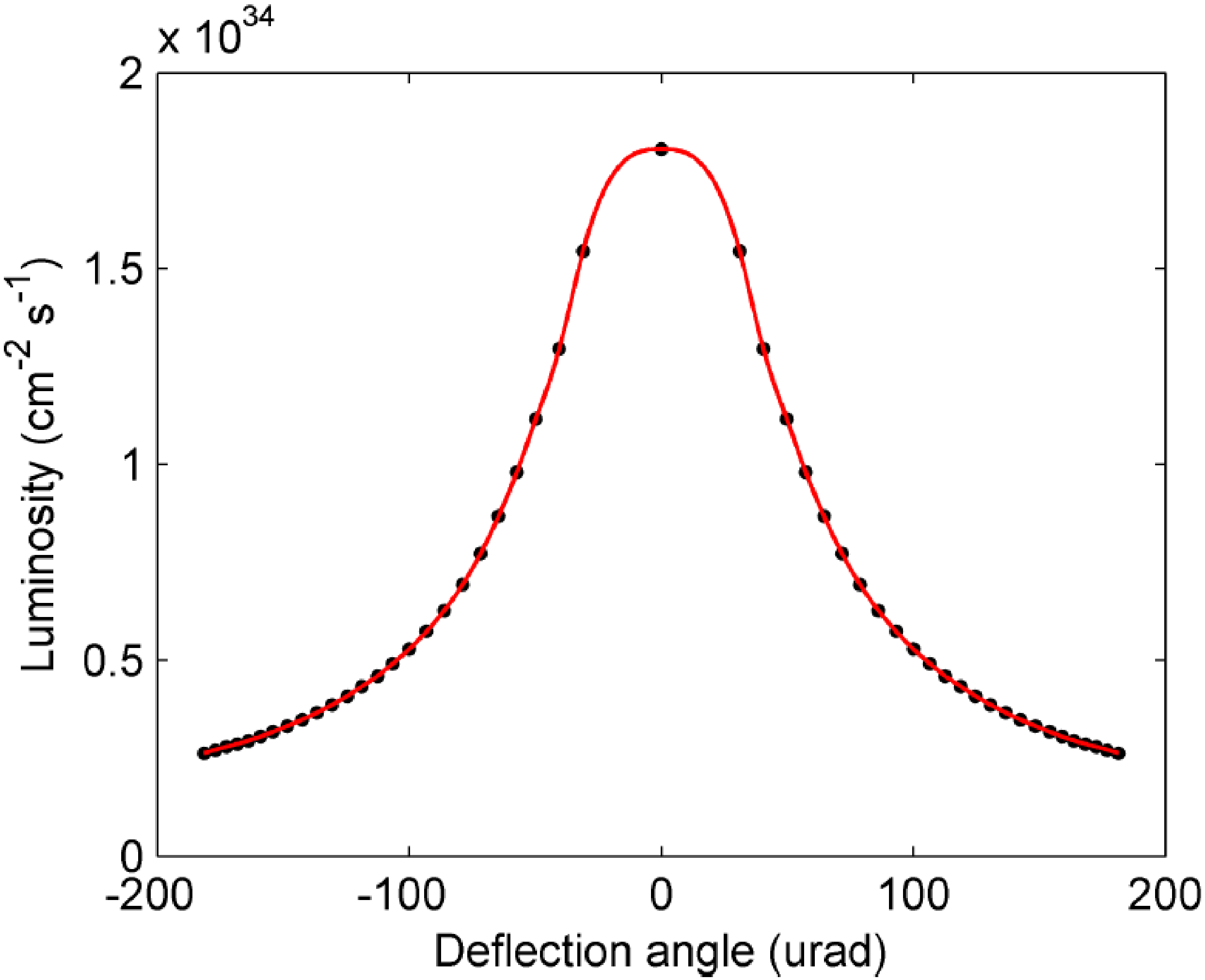
FONT – Feedback On Nanosecond Timescales:

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

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

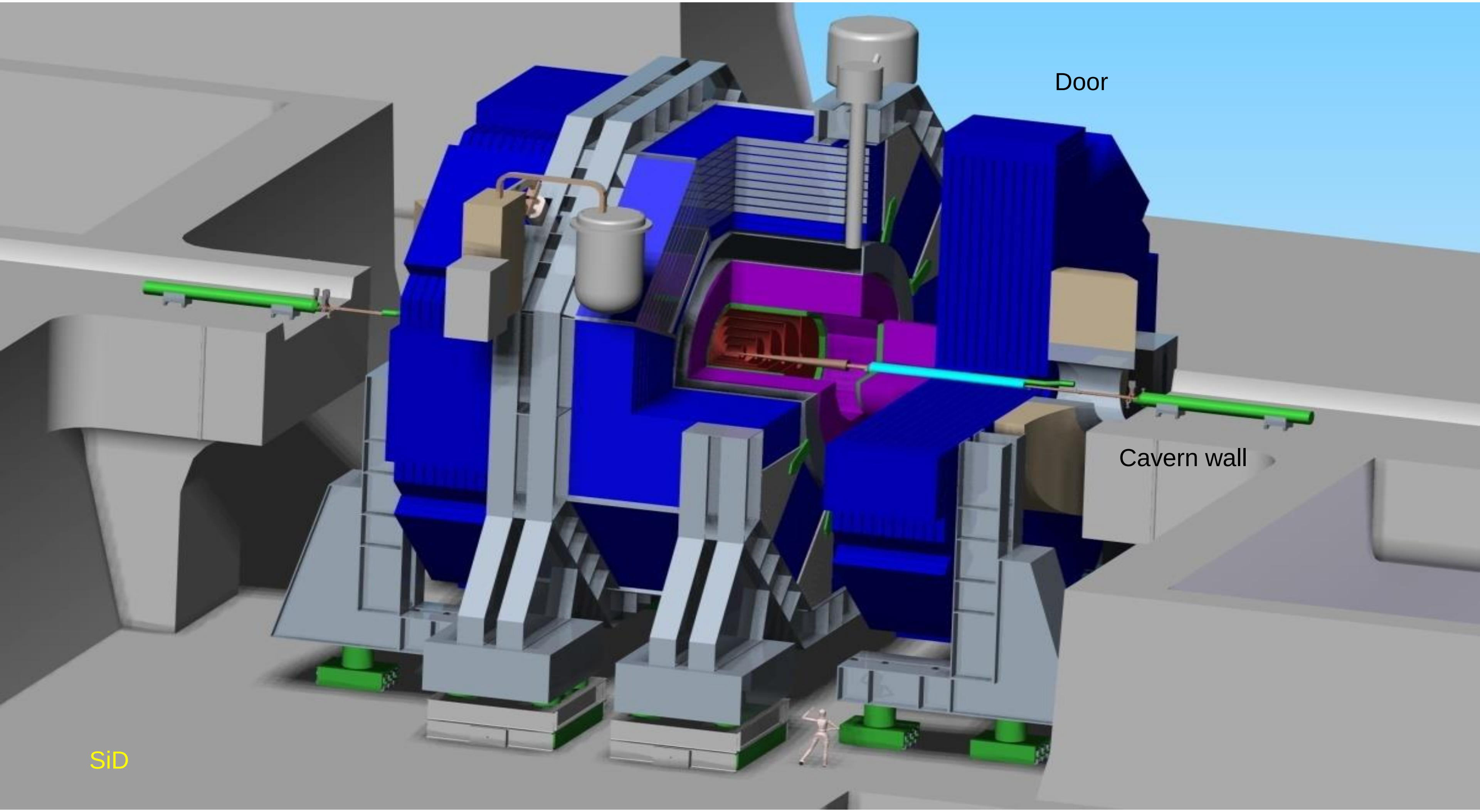
2. IP beam angle feedback: hardware located few 100 metres upstream

conceptually very similar to position FB, less critical

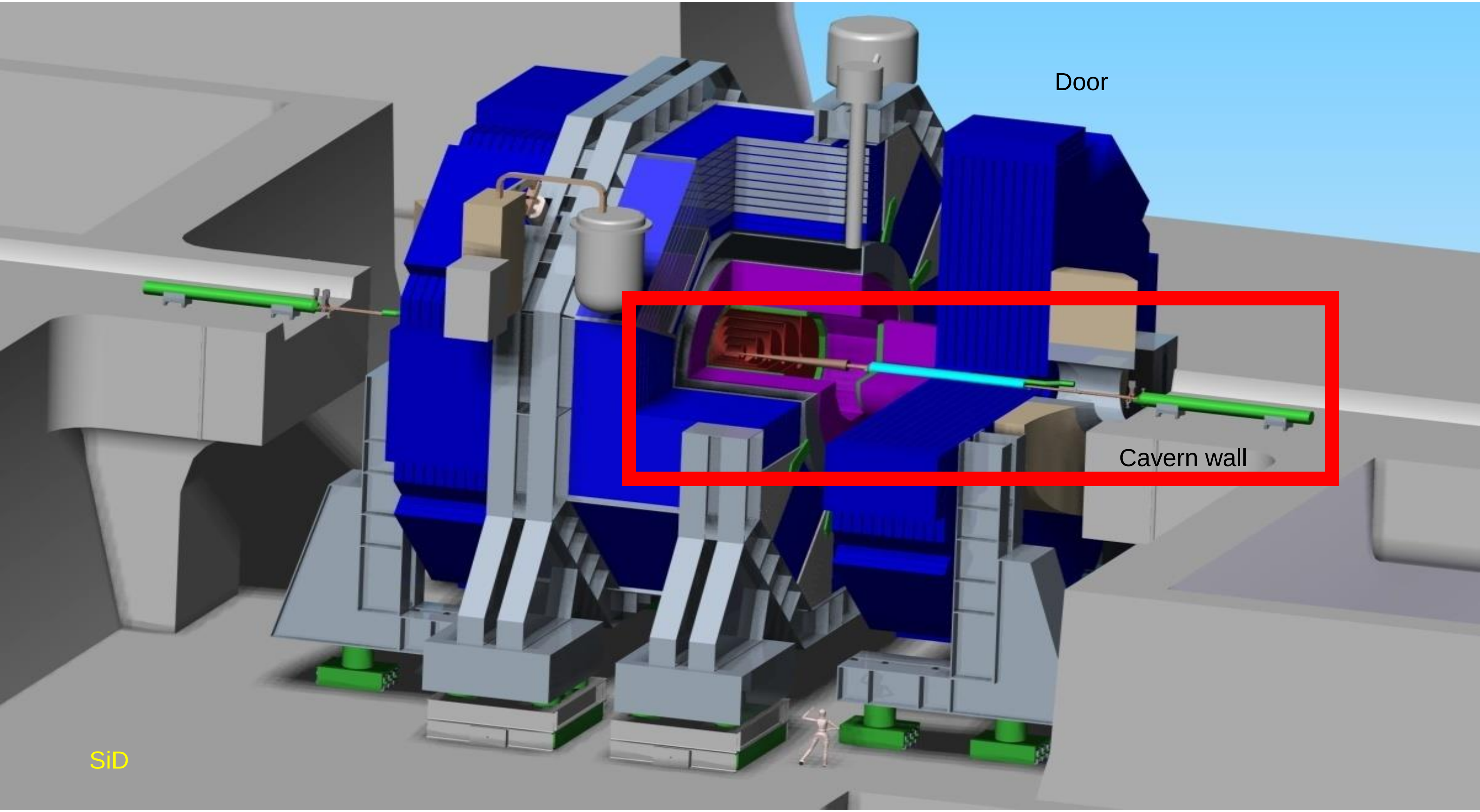
3. Bunch-by-bunch luminosity signal (from 'BEAMCAL')

'special' systems requiring dedicated hardware + data links

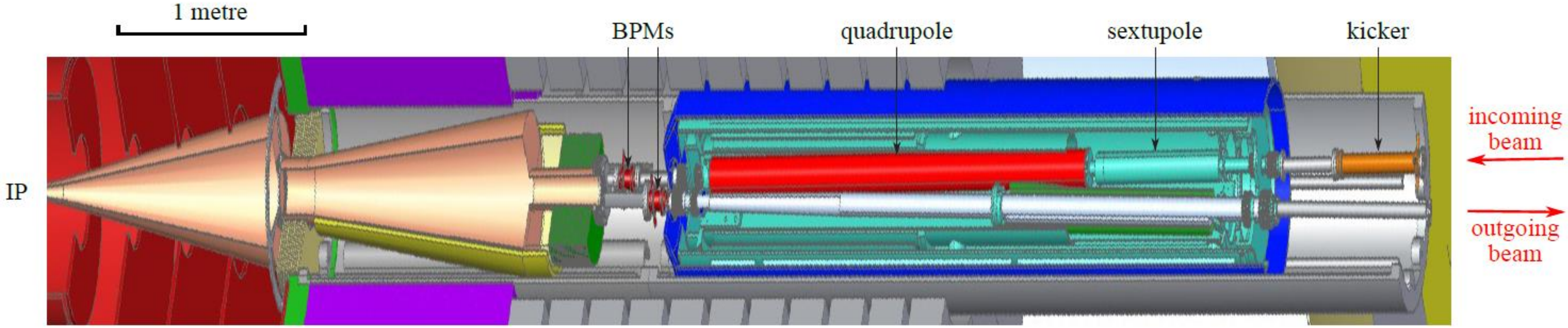
ILC Interaction Region (SiD)



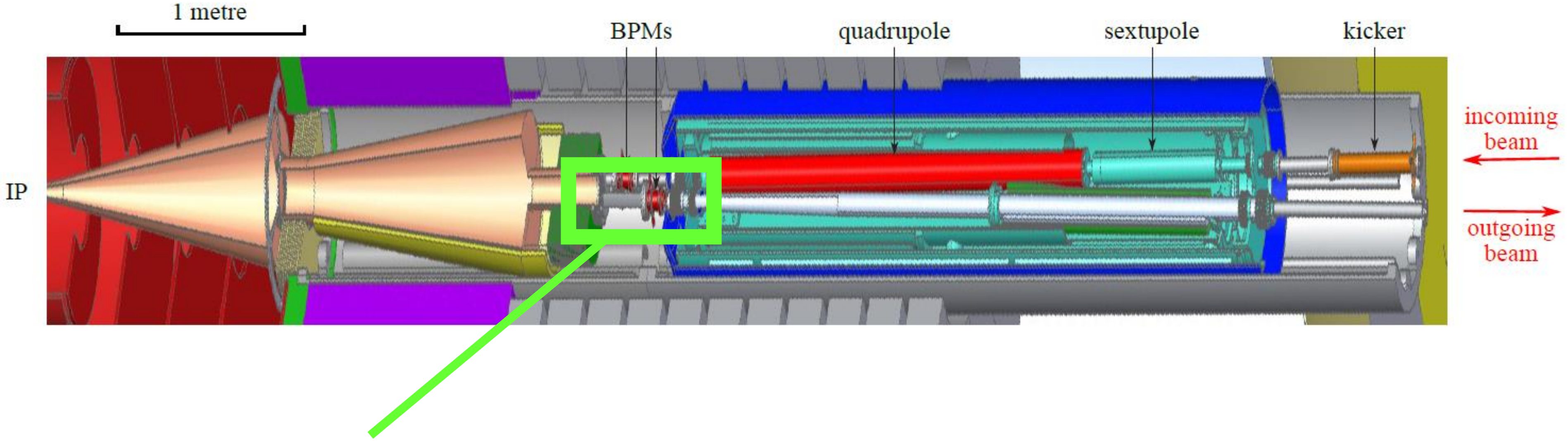
ILC Interaction Region (SiD)



Final-focus region (SiD)



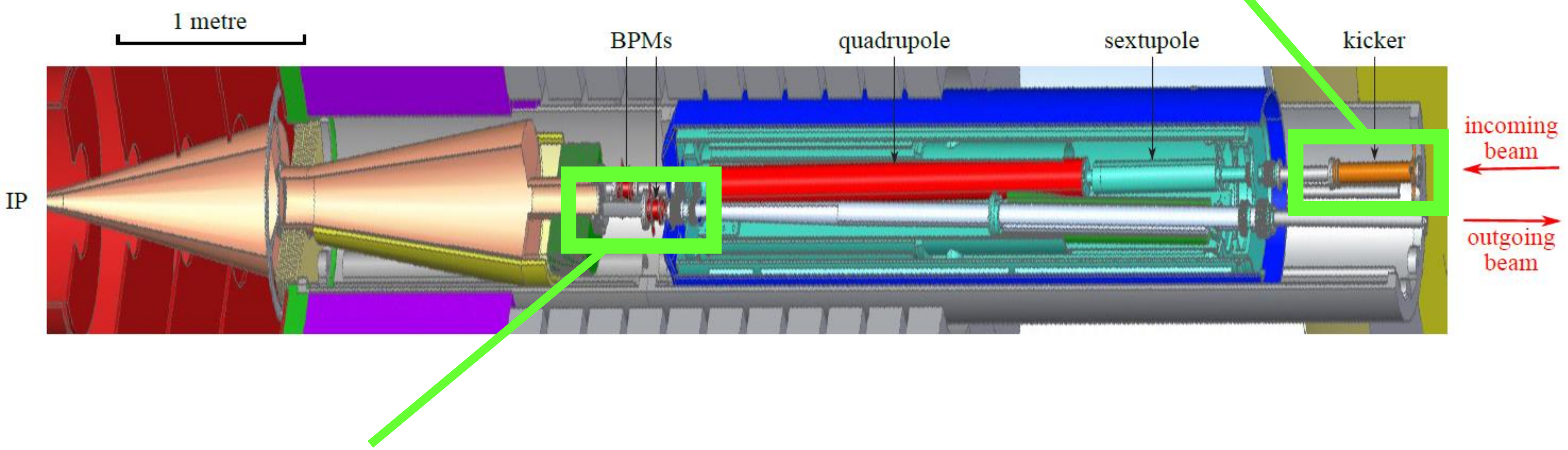
Final-focus region (SiD)



FB BPM on outgoing beamline

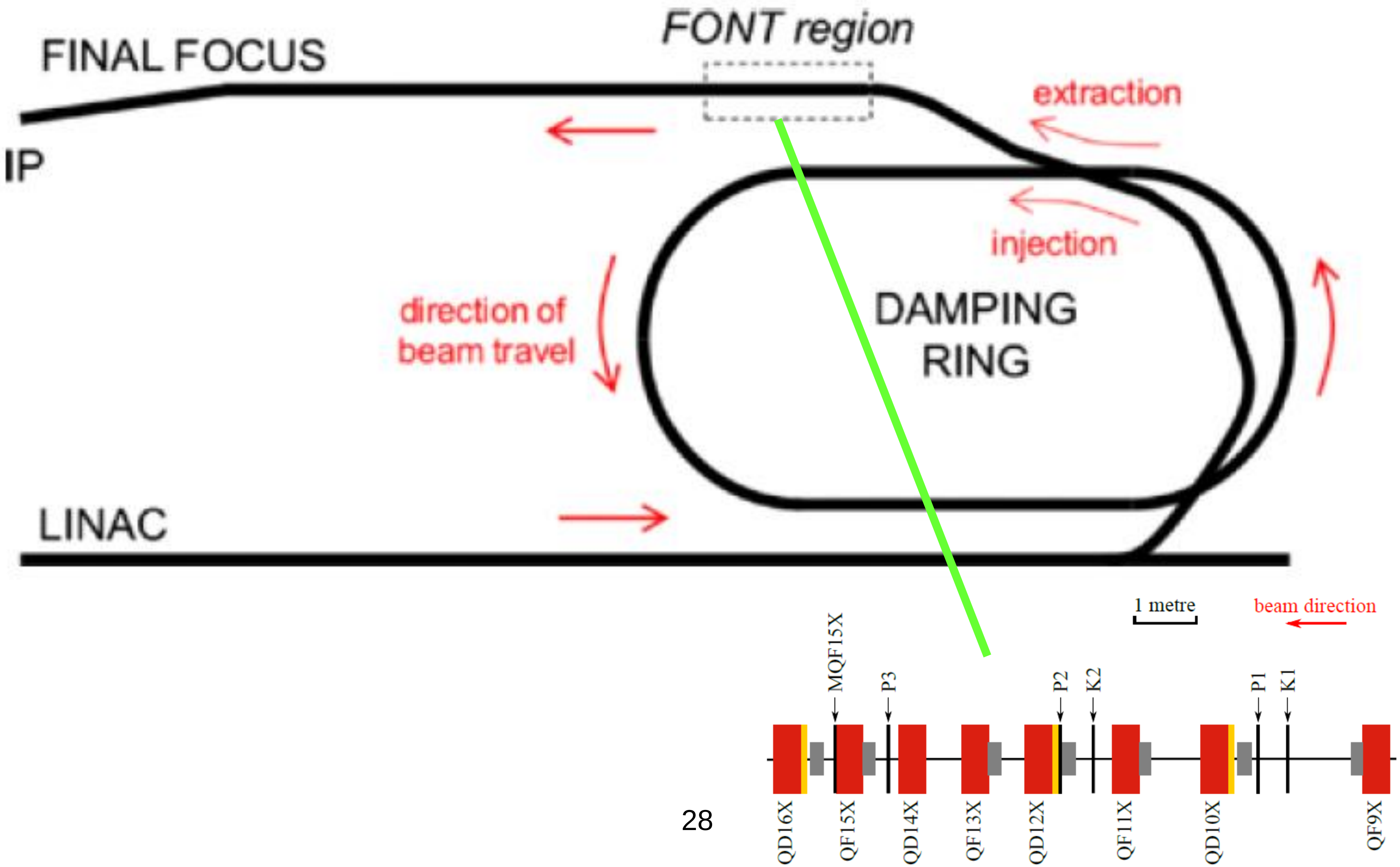
Final-focus region (SiD)

FB kicker on incoming beamline

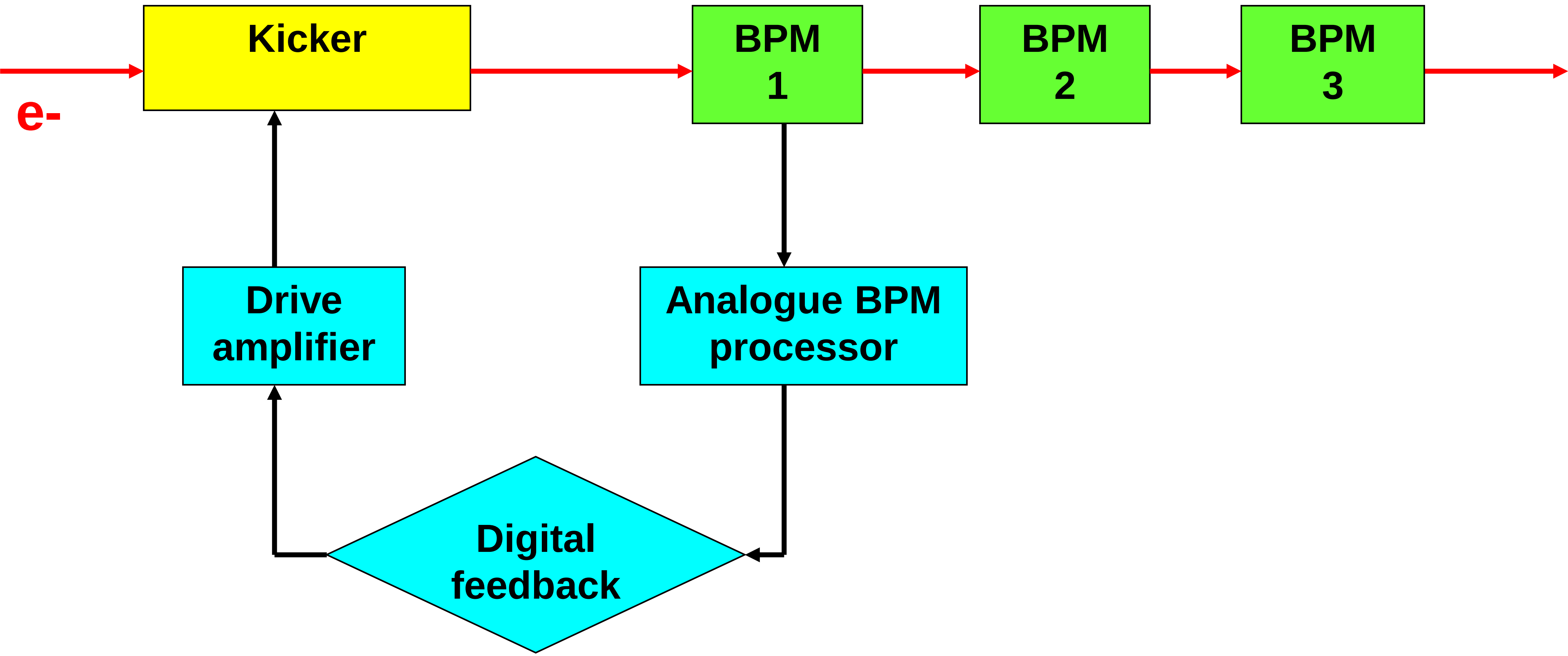


BPM on outgoing beamline

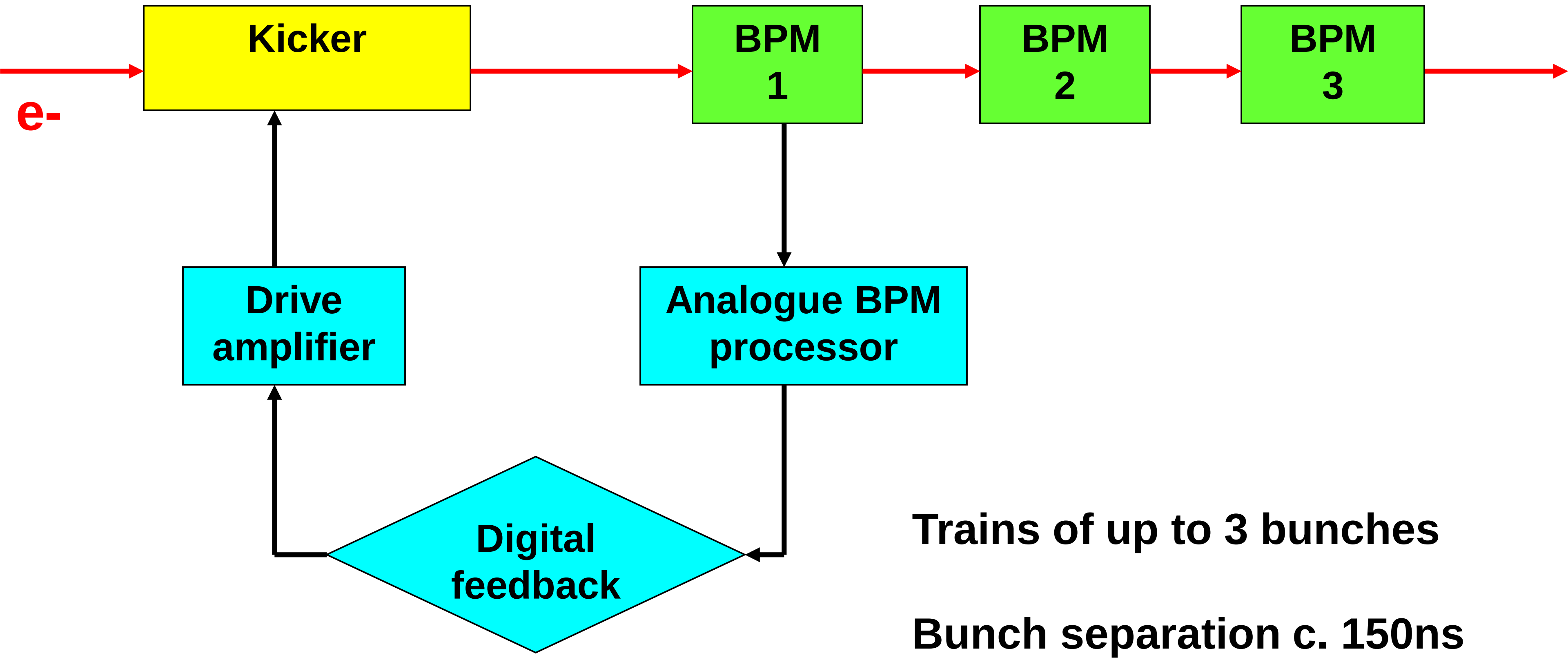
KEK Accelerator Test Facility (ATF2)



ILC FB prototype: FONT at KEK/ATF



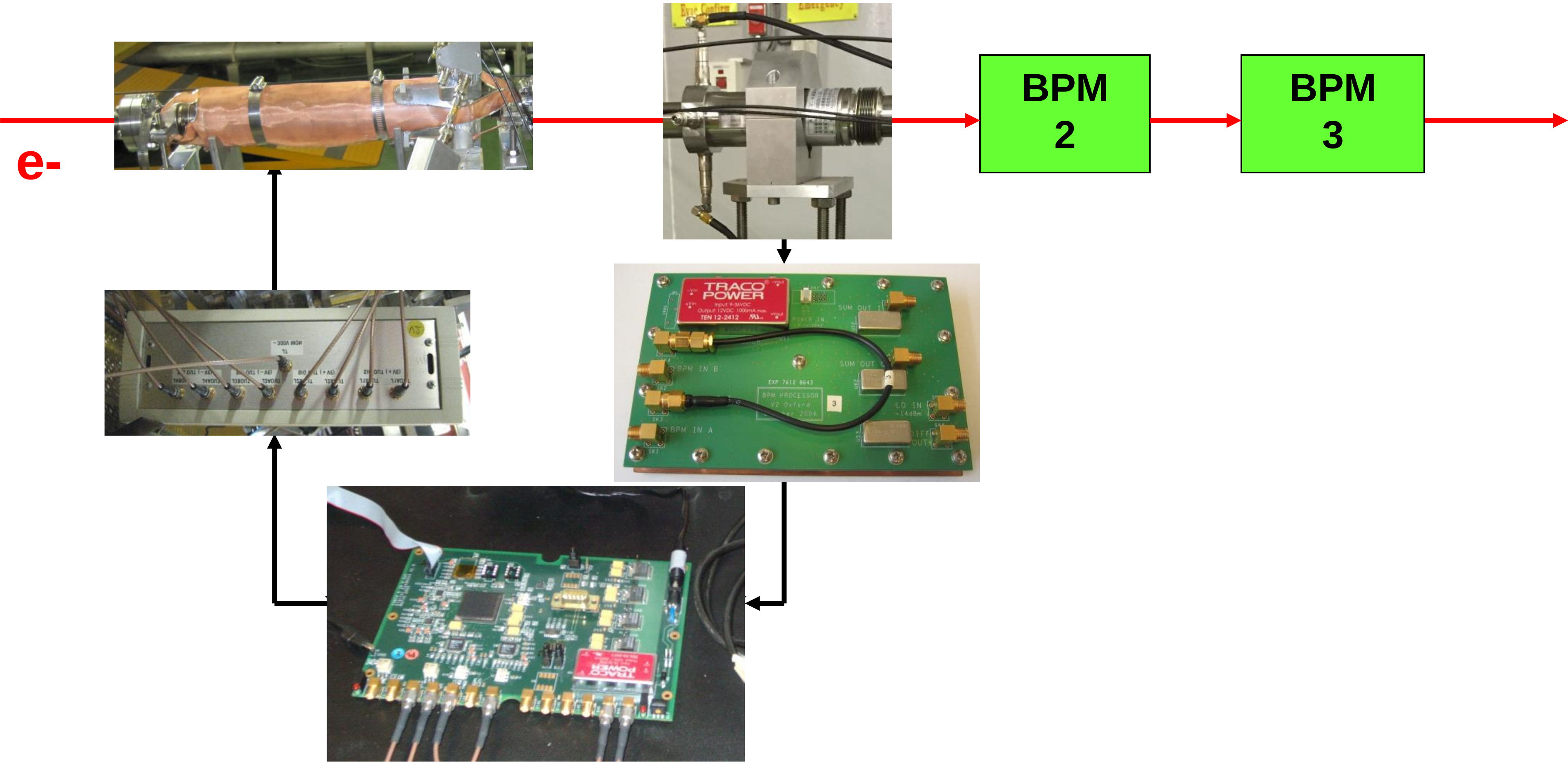
ILC FB prototype: FONT at KEK/ATF



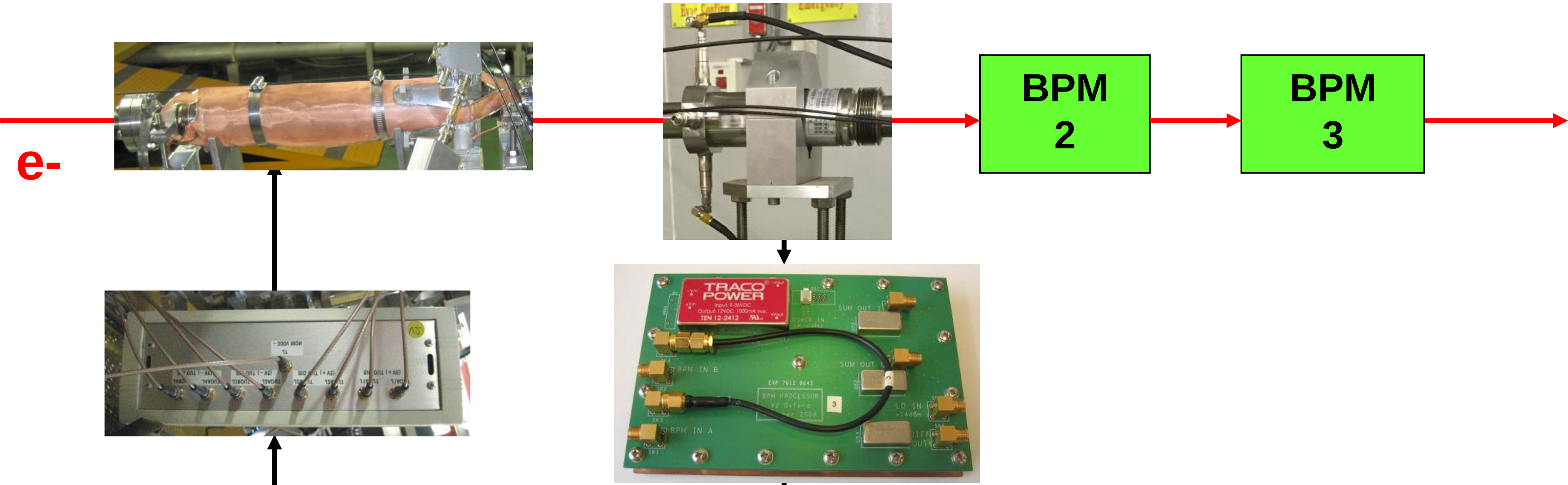
Trains of up to 3 bunches

Bunch separation c. 150ns

ILC prototype: FONT4 at KEK/ATF



ILC prototype: FONT4 at KEK/ATF

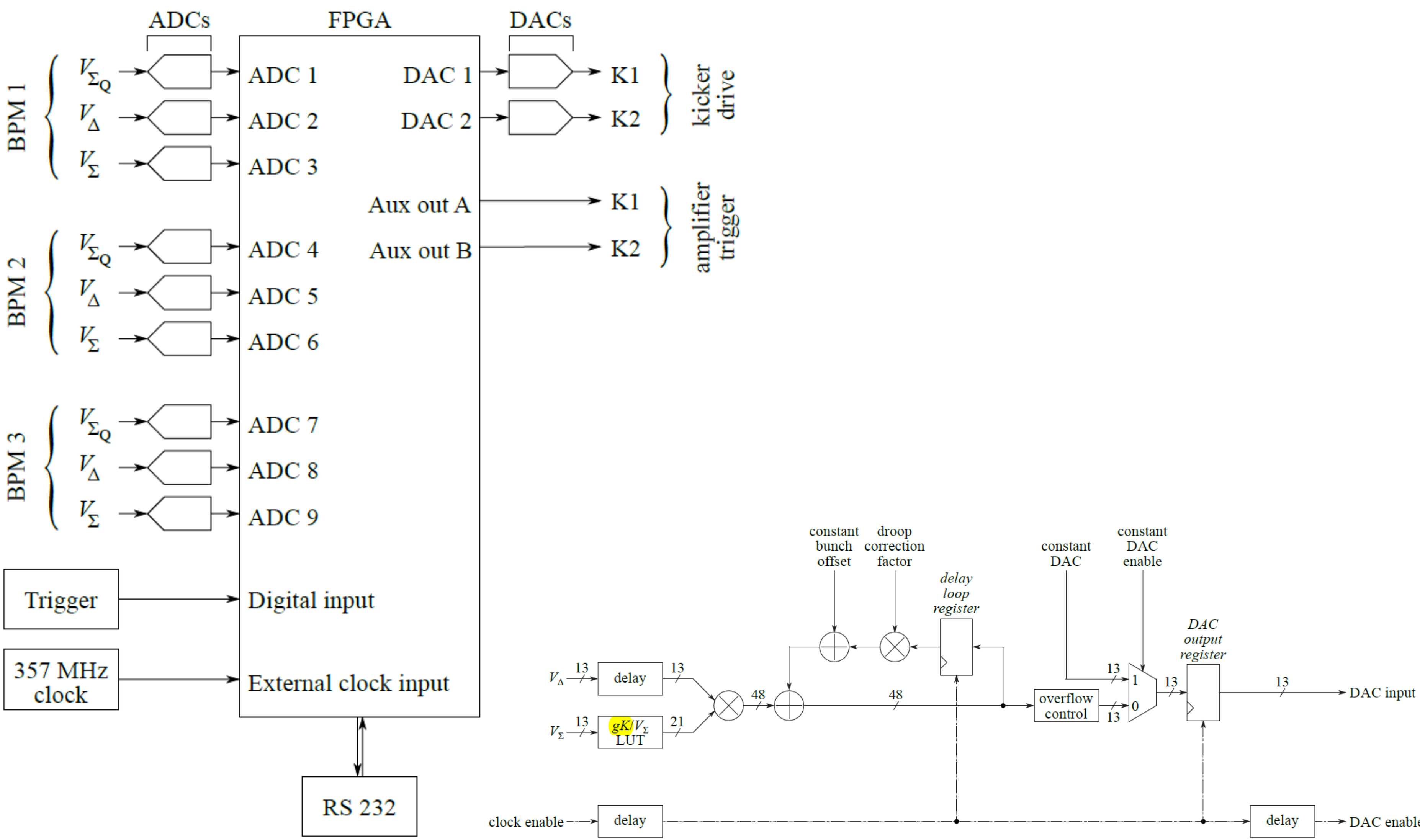


BPM resolution ~ 0.3um

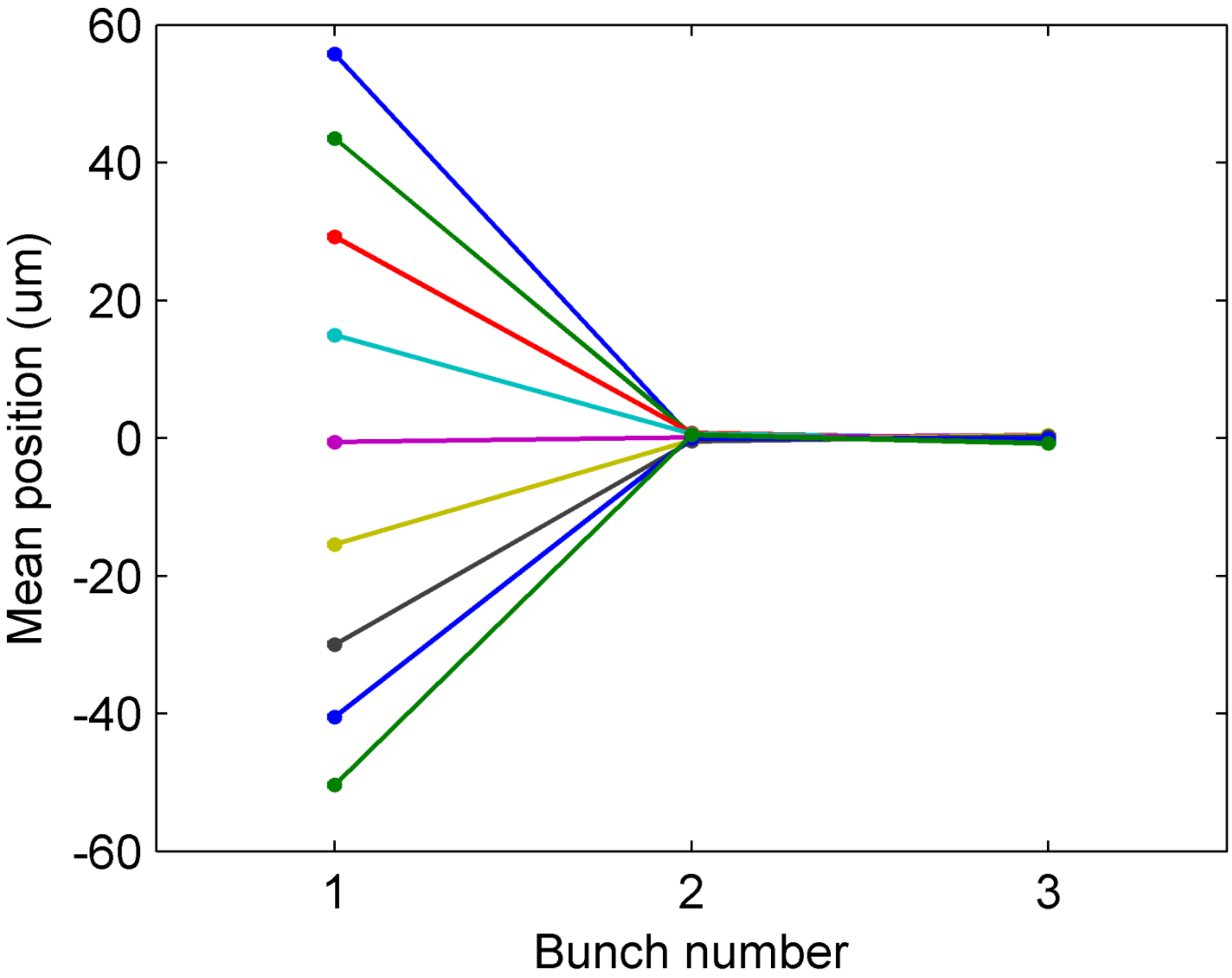
Latency ~ 150ns

Drive power > 300nm @ ILC

FONT digital feedback board



FONT ILC prototype performance



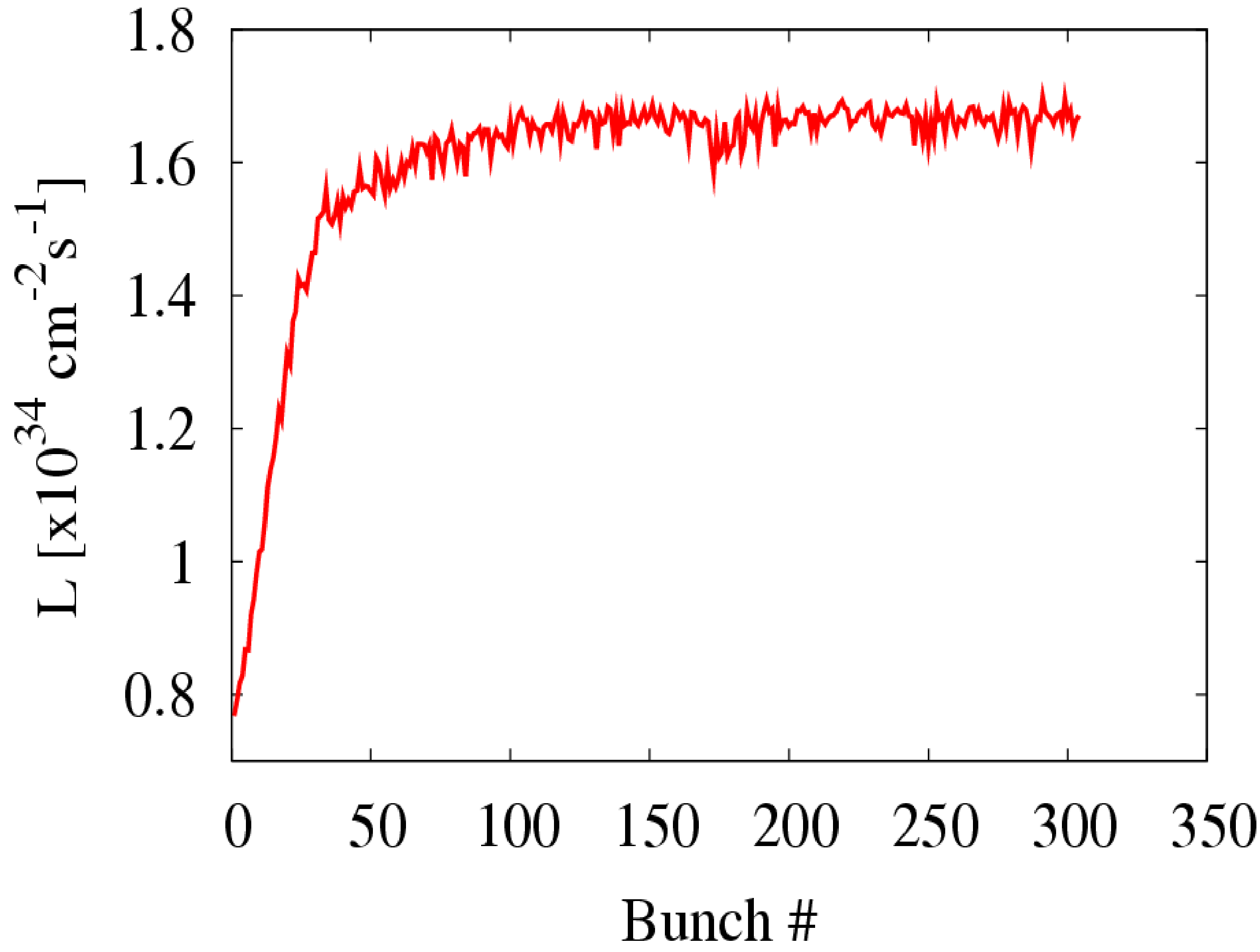
FONT ILC prototype performance

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	$\sim \pm 60$	$\sim \pm 180^\dagger$

† scaled by the ATF/ILC beam energy ratio

Simulated ILC IP FB performance



IP FB Design Status: CLIC

Conceptual design developed and documented in CLIC CDR (2012)

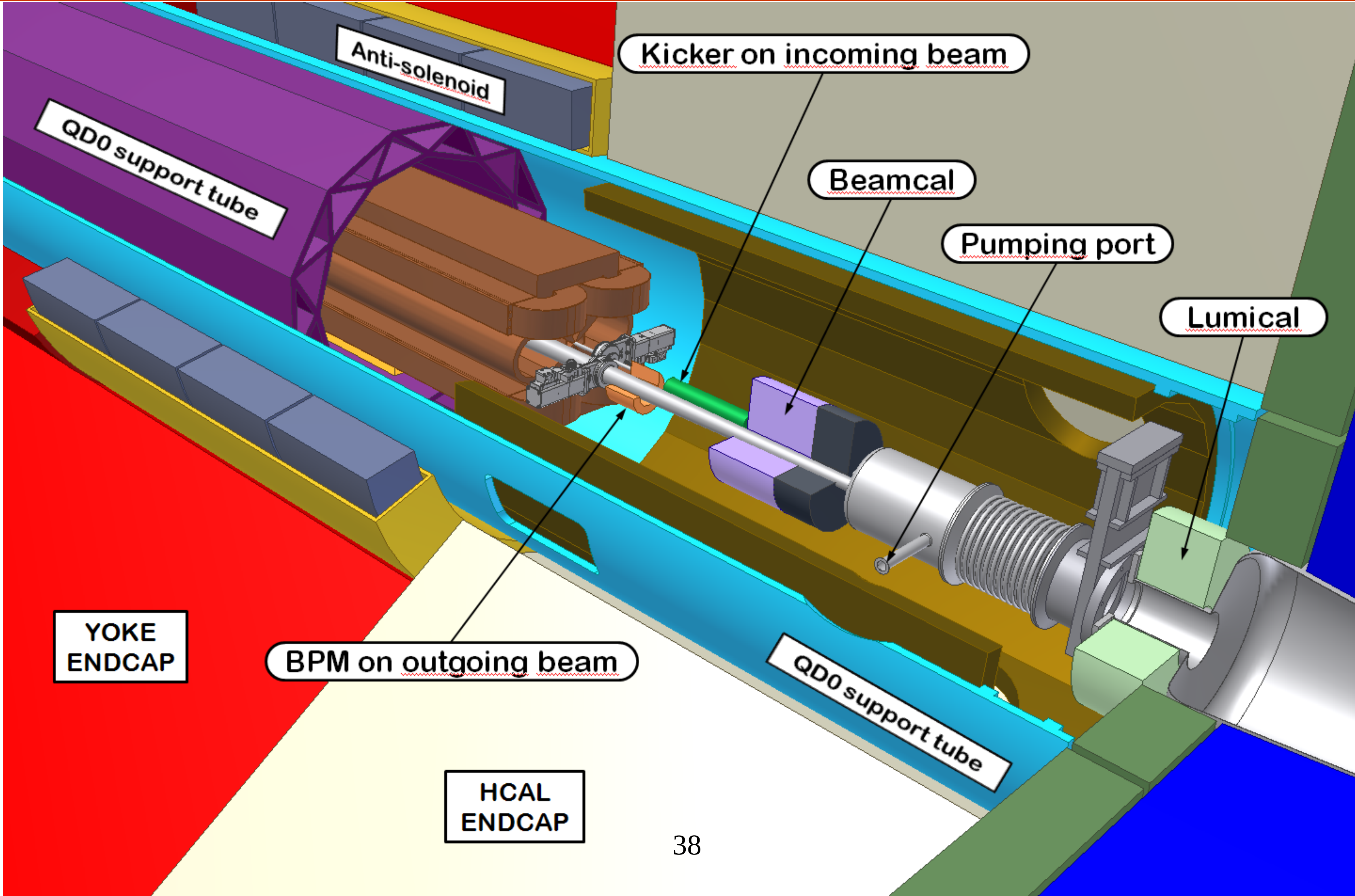
NB primary method for control of beam collision overlap is via vibration isolation of the FF magnets, and dynamic correction of residual component motions

IP position feedback:

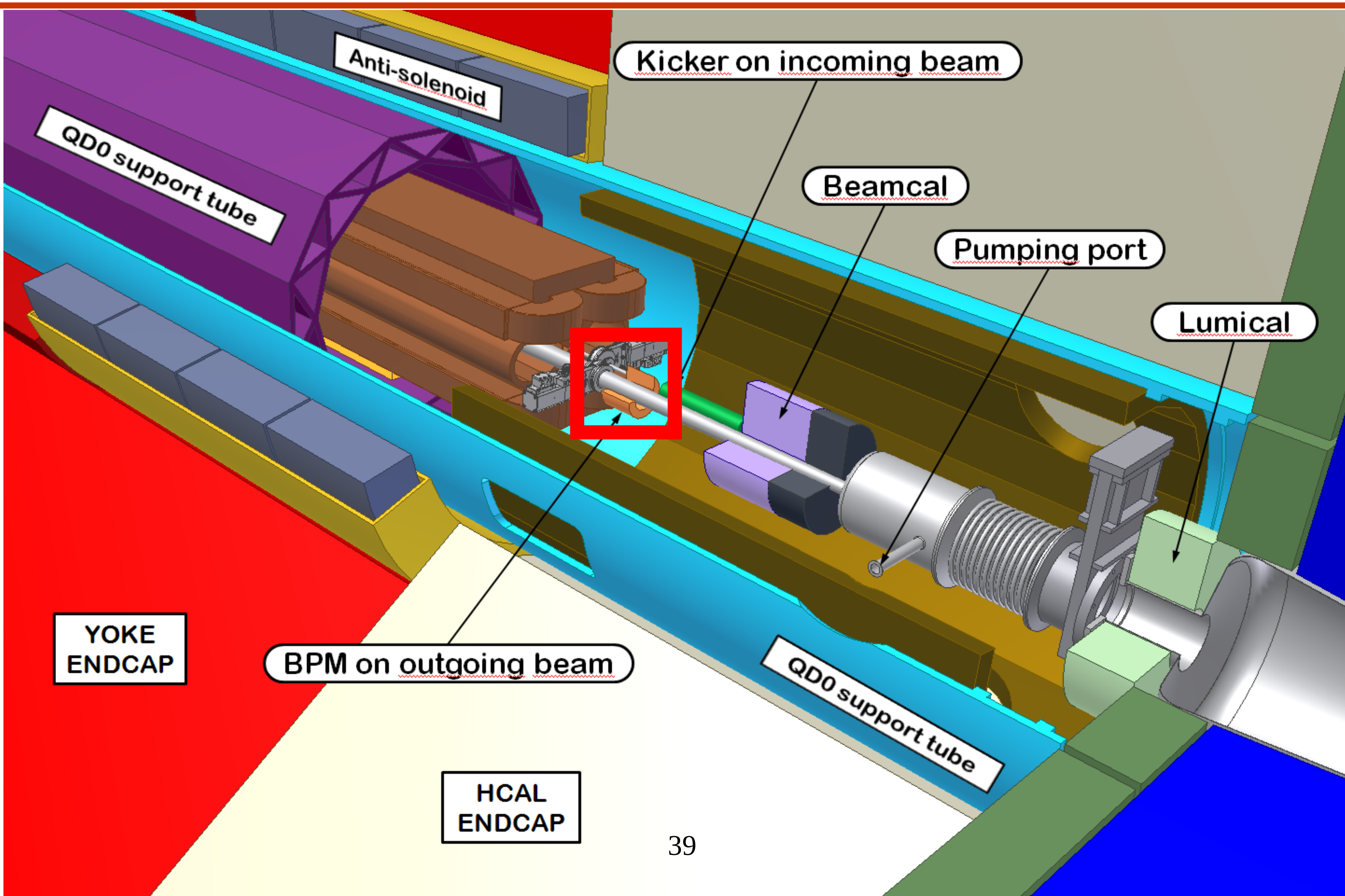
beam position correction up to +- 50 nm vertical at IP

More realistic engineering design being developed now

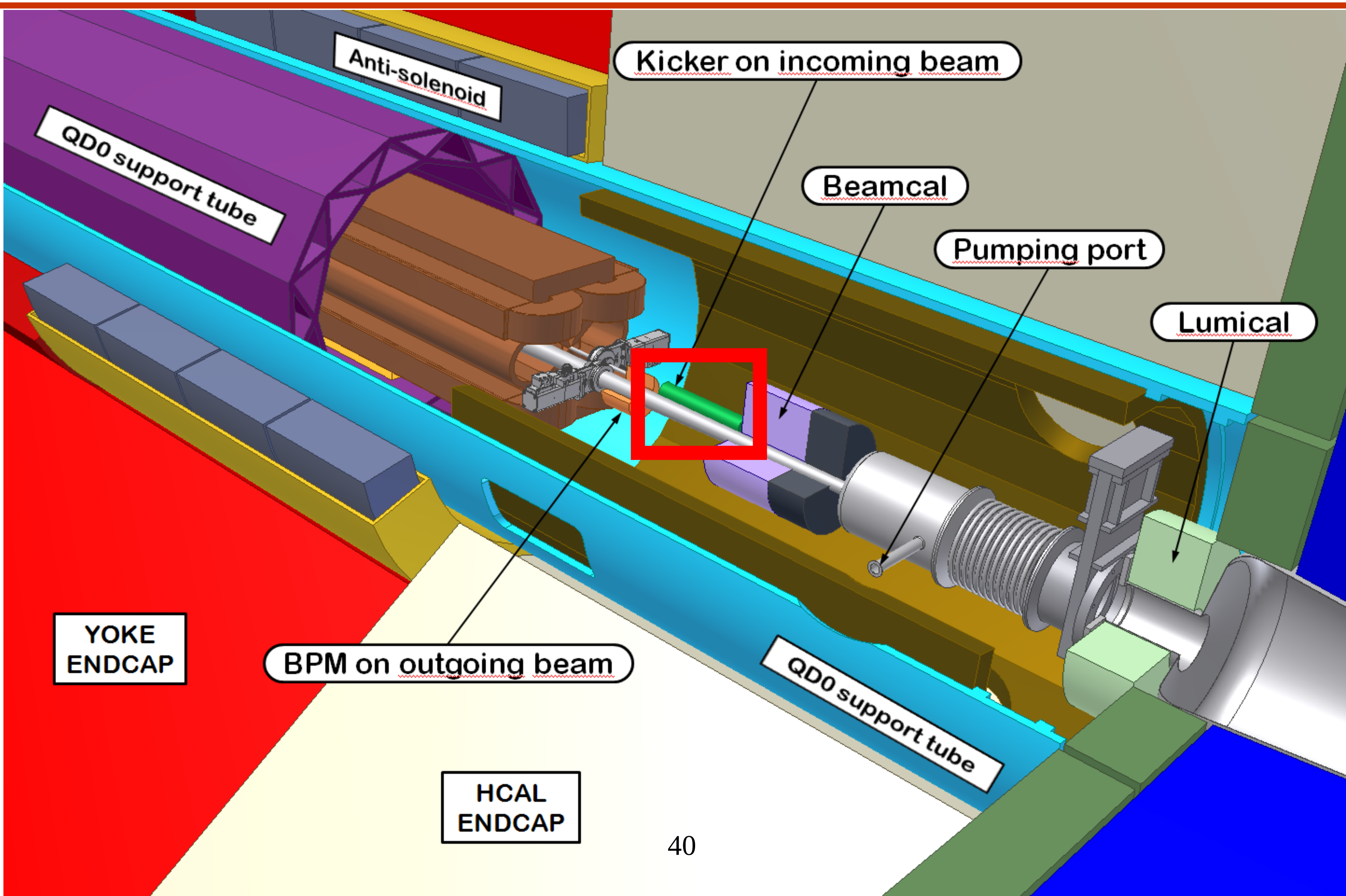
CLIC Final Doublet Region



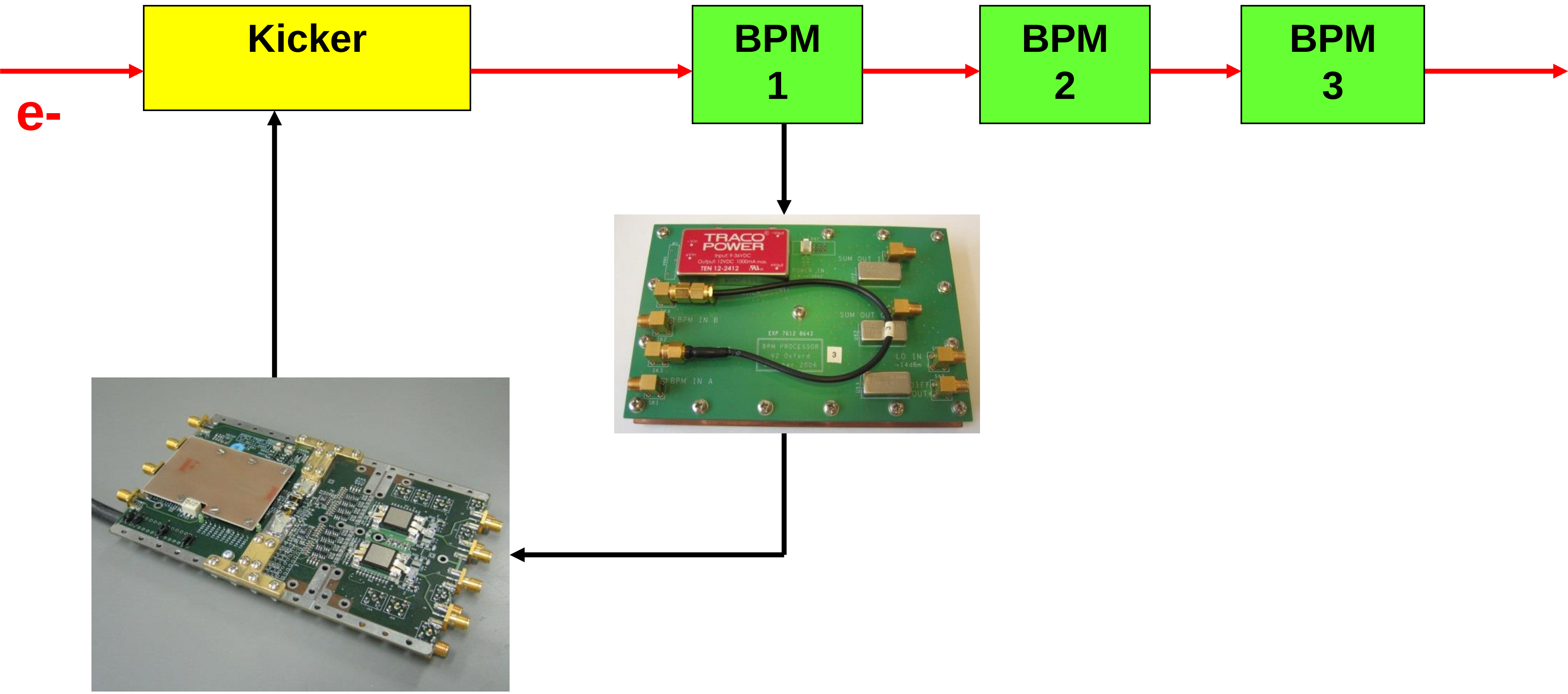
CLIC Final Doublet Region



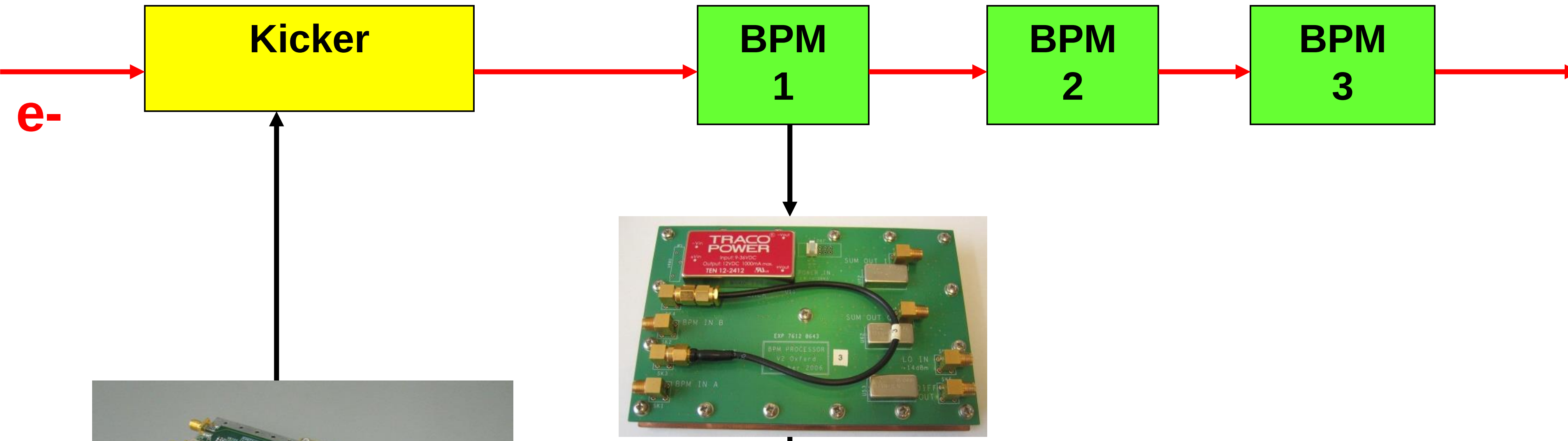
CLIC Final Doublet Region

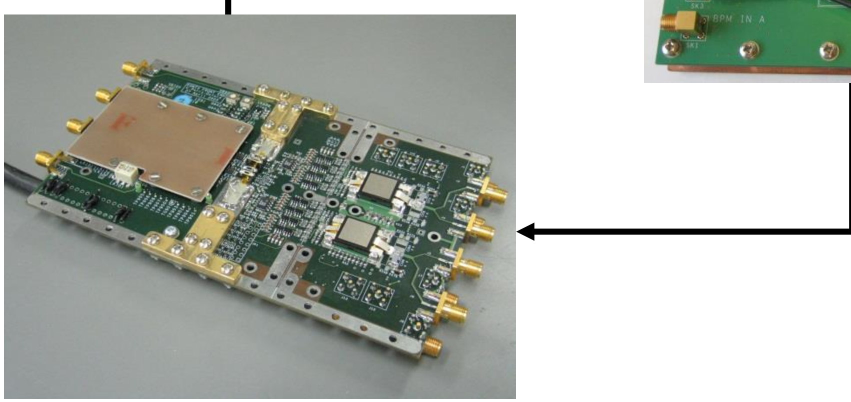


CLIC prototype: FONT3 at KEK/ATF



CLIC prototype: FONT3 at KEK/ATF

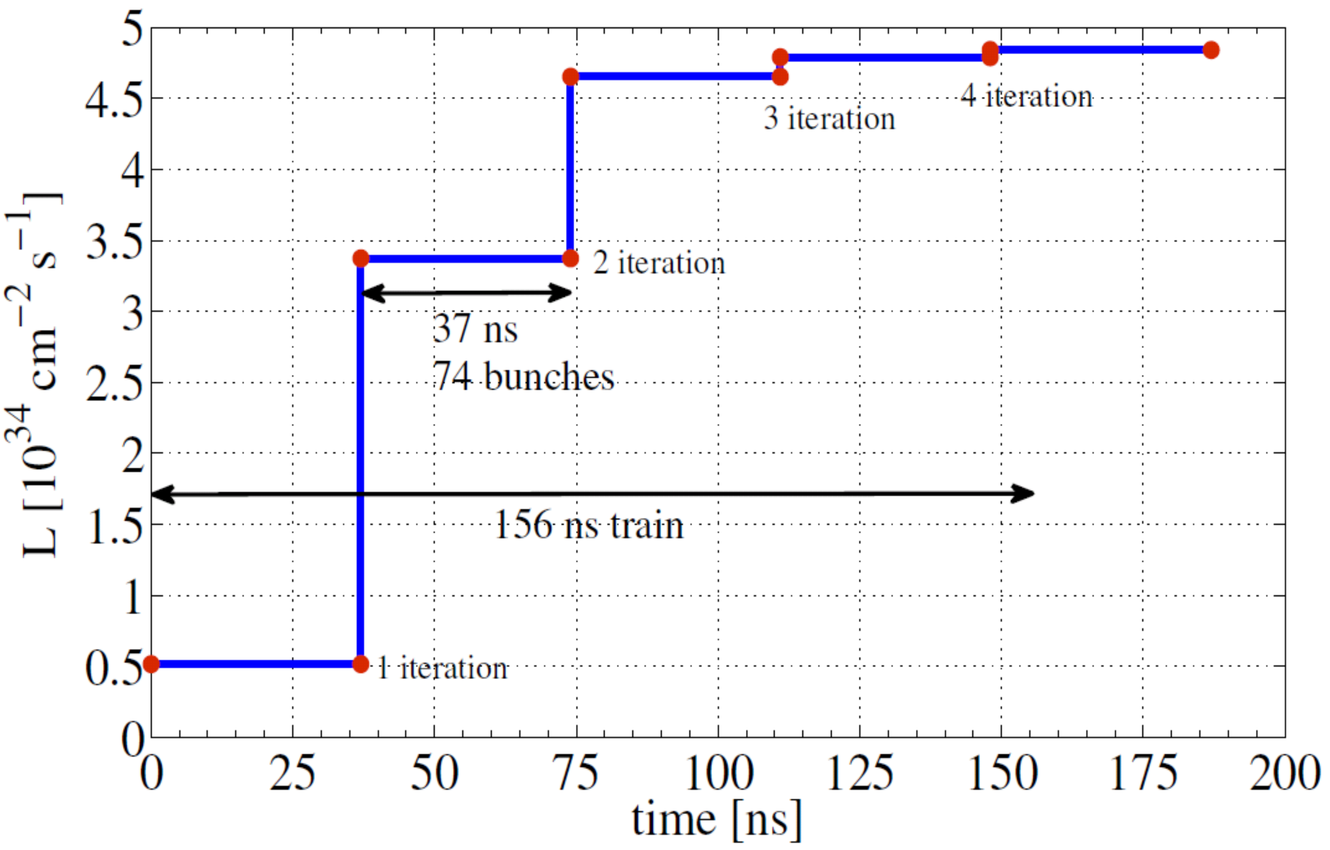




Electronics latency ~ 13ns
Drive power > 50nm @ CLIC

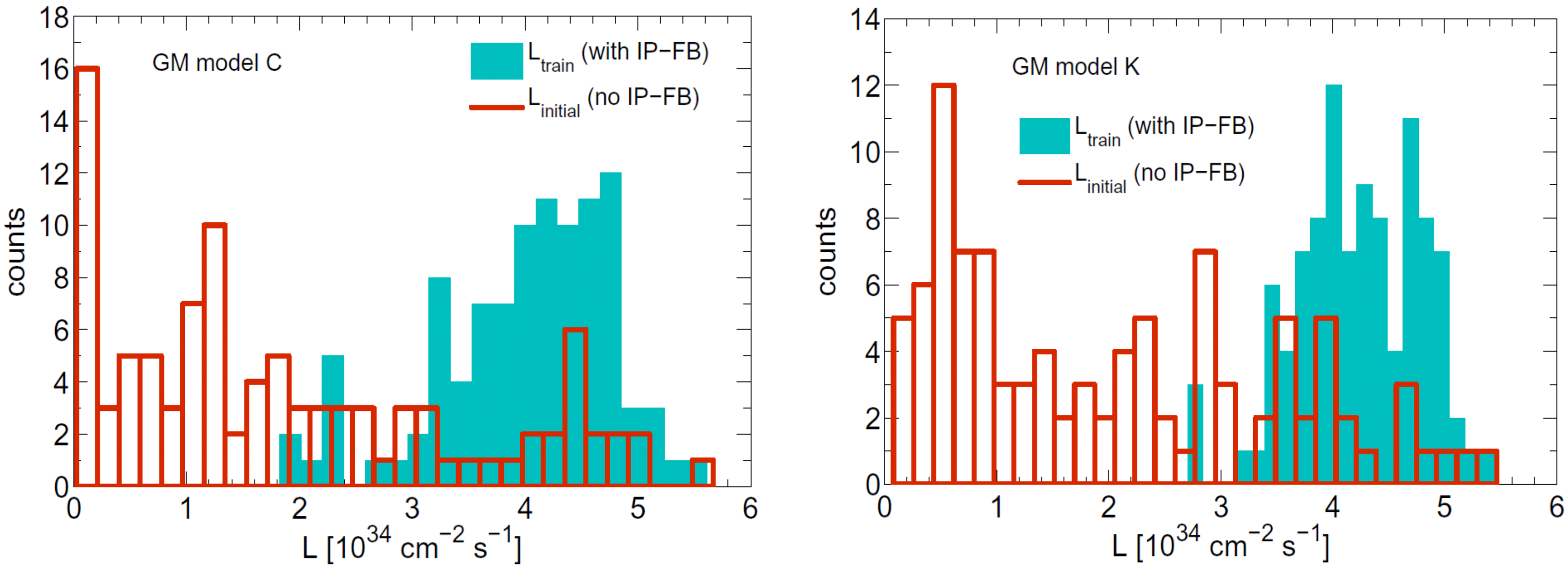
CLIC IP FB performance

Single random seed of GM C



CLIC IP FB performance

For noisy sites:



→ factor 2 - 3 improvement

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

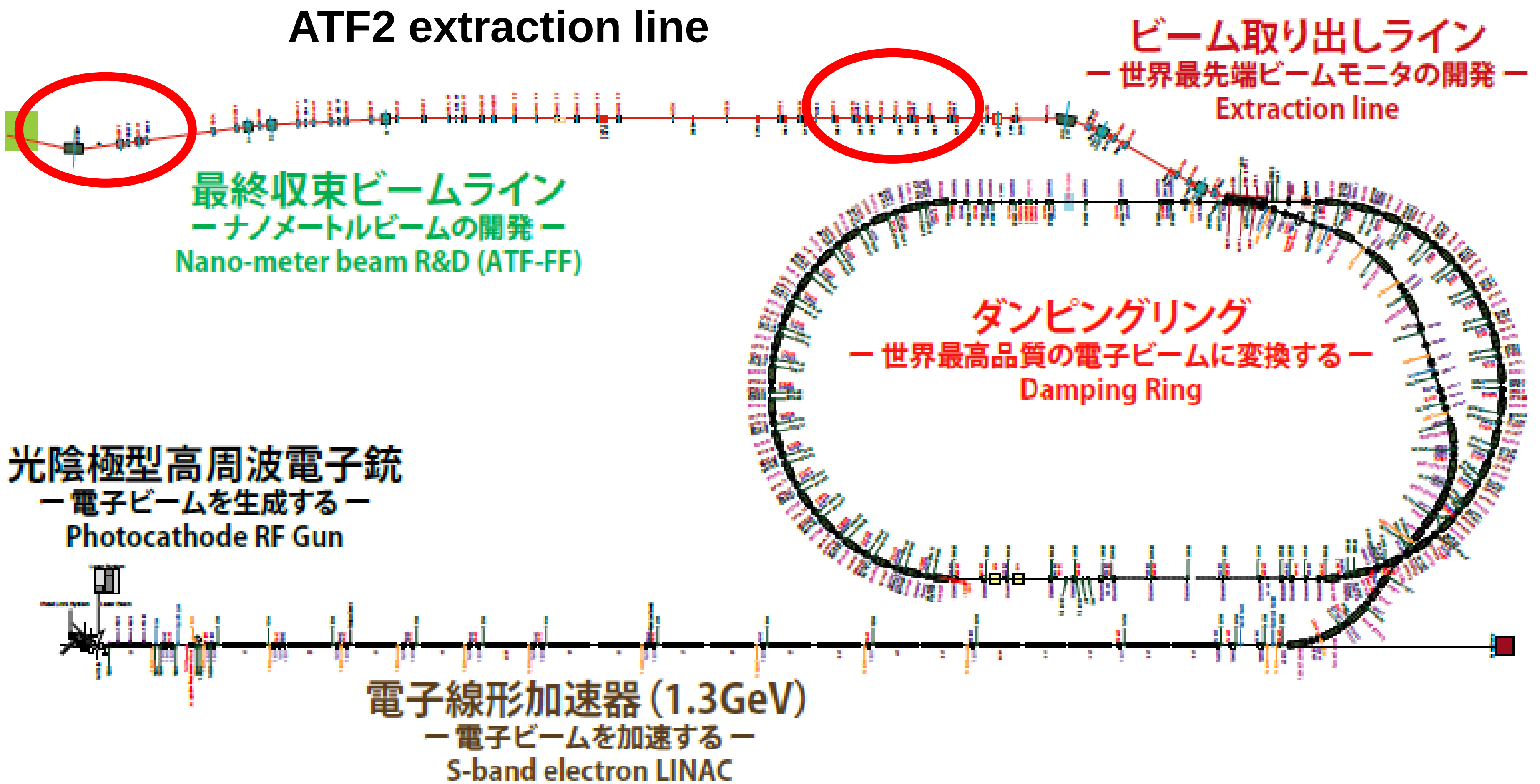
Summary for ILC + CLIC

- **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**

Latest beam stabilisation results from ATF2

- **Beam size ~ 41 nm achieved (ATF2 goal 1)**
- **Direct stabilisation of small beam at nm level (ATF2 goal 2)**
- **A FB loop has been installed at ATF2 IP for direct stabilisation of the beam locally**
- **This is MUCH harder than IPFB at ILC/CLIC as there is only 1 beam, which must be directly measured with nm resolution!**
- **Nevertheless it is an interesting challenge …**
- **High-resolution BPMs required in CLIC BDS**

FONT5 installation at ATF2



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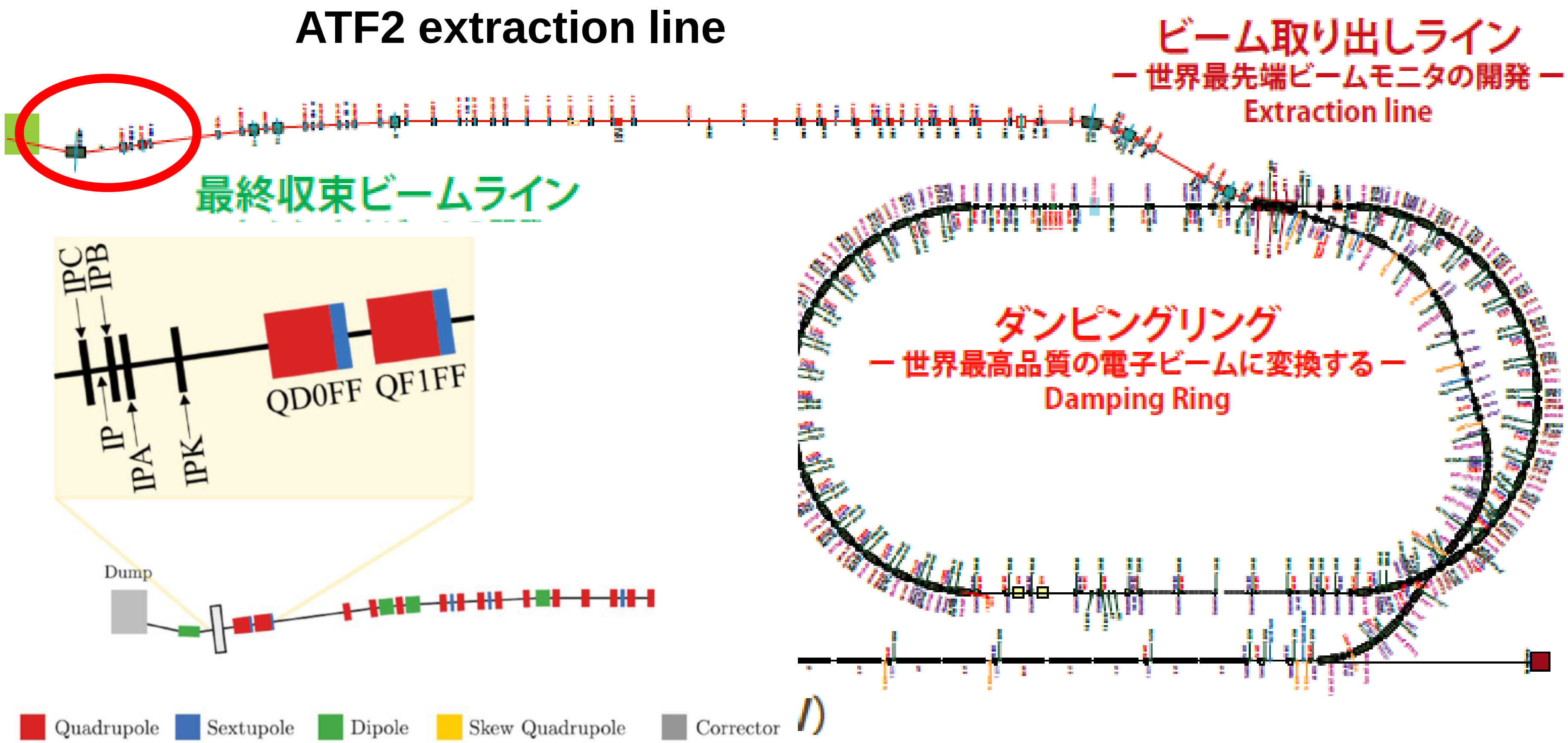
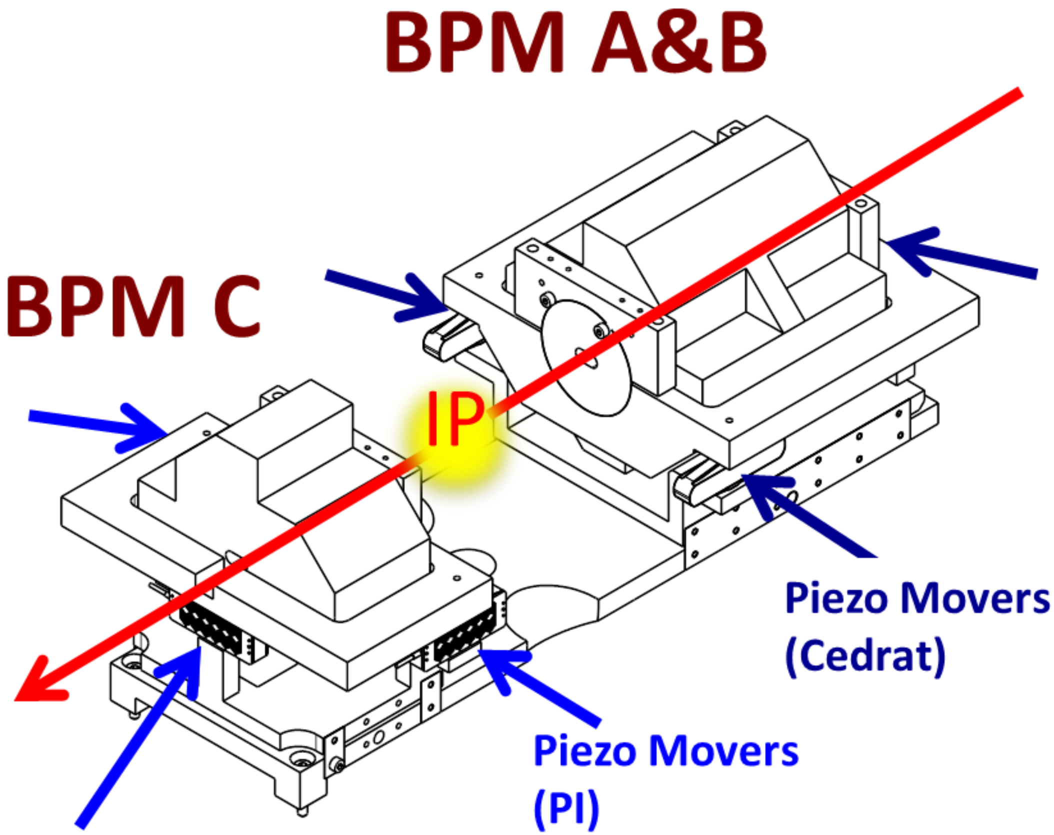


FONT IP feedback system with kicker IPK, cavity BPMs: IPA, IPB and IPC, and final focus quadrupoles QD0FF and QF1FF.

IP chamber including 3 cavity BPMs

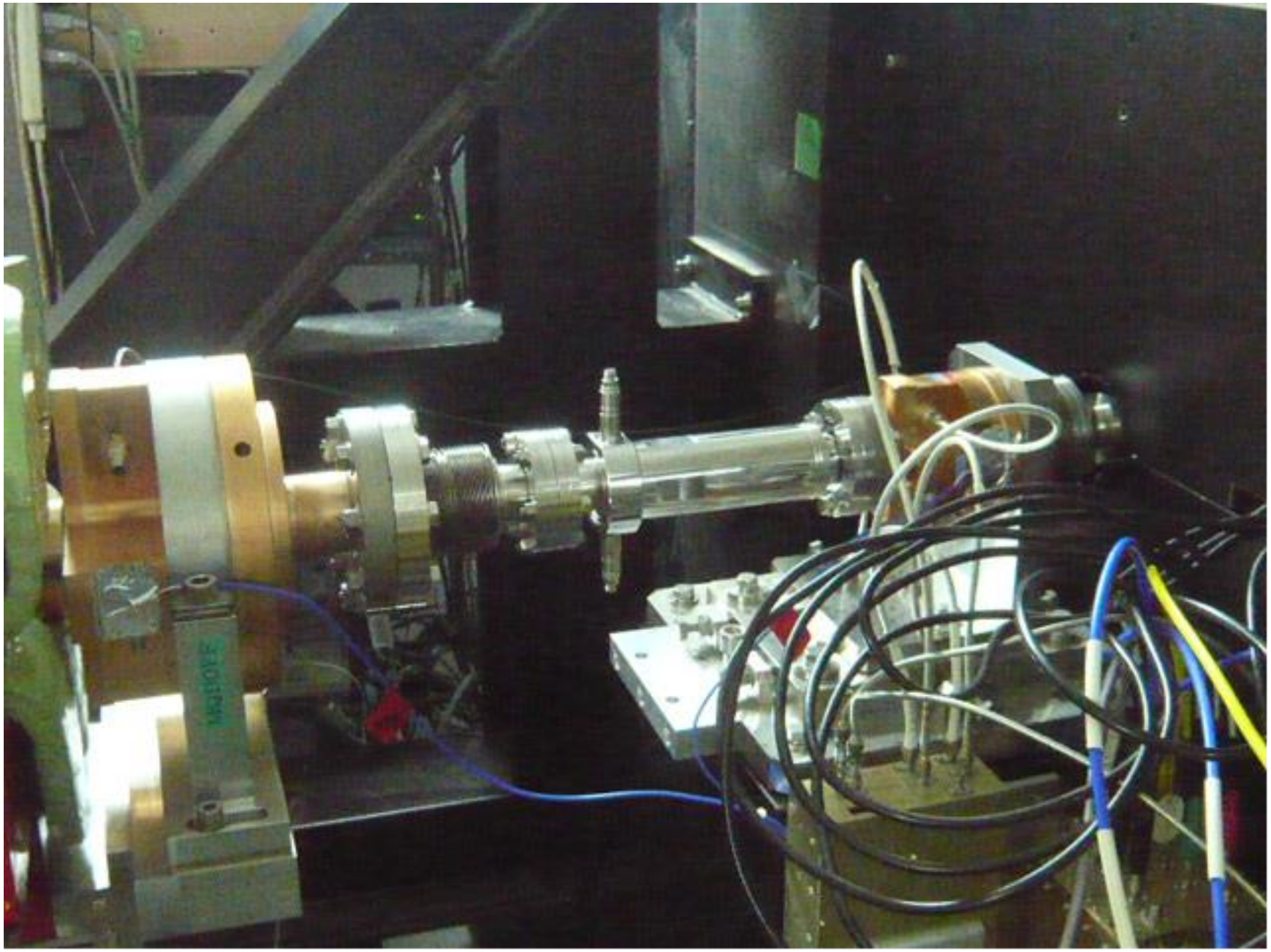


JAI, KEK, KNU, LAL

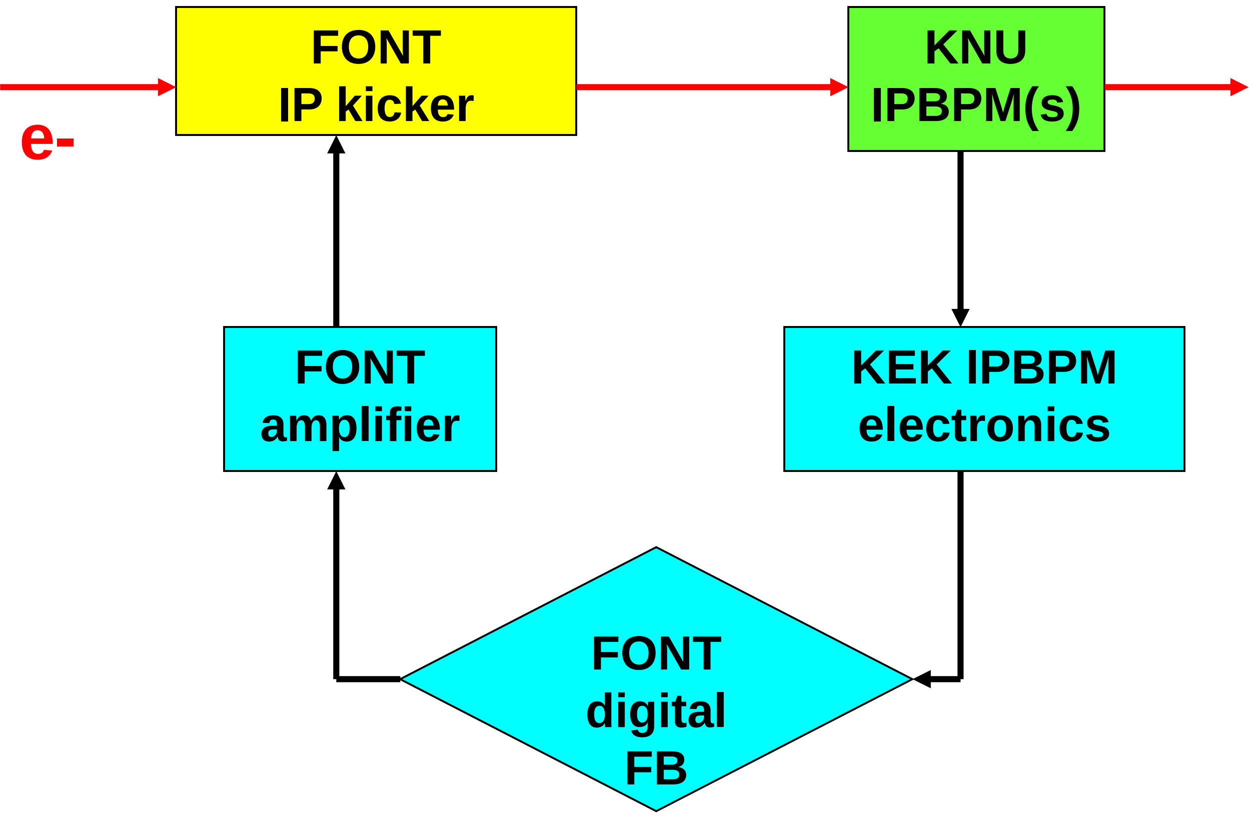
3 cavity BPMs

Mover system for BPM alignment

Compact IP kicker



ATF2 'IPFB' tests



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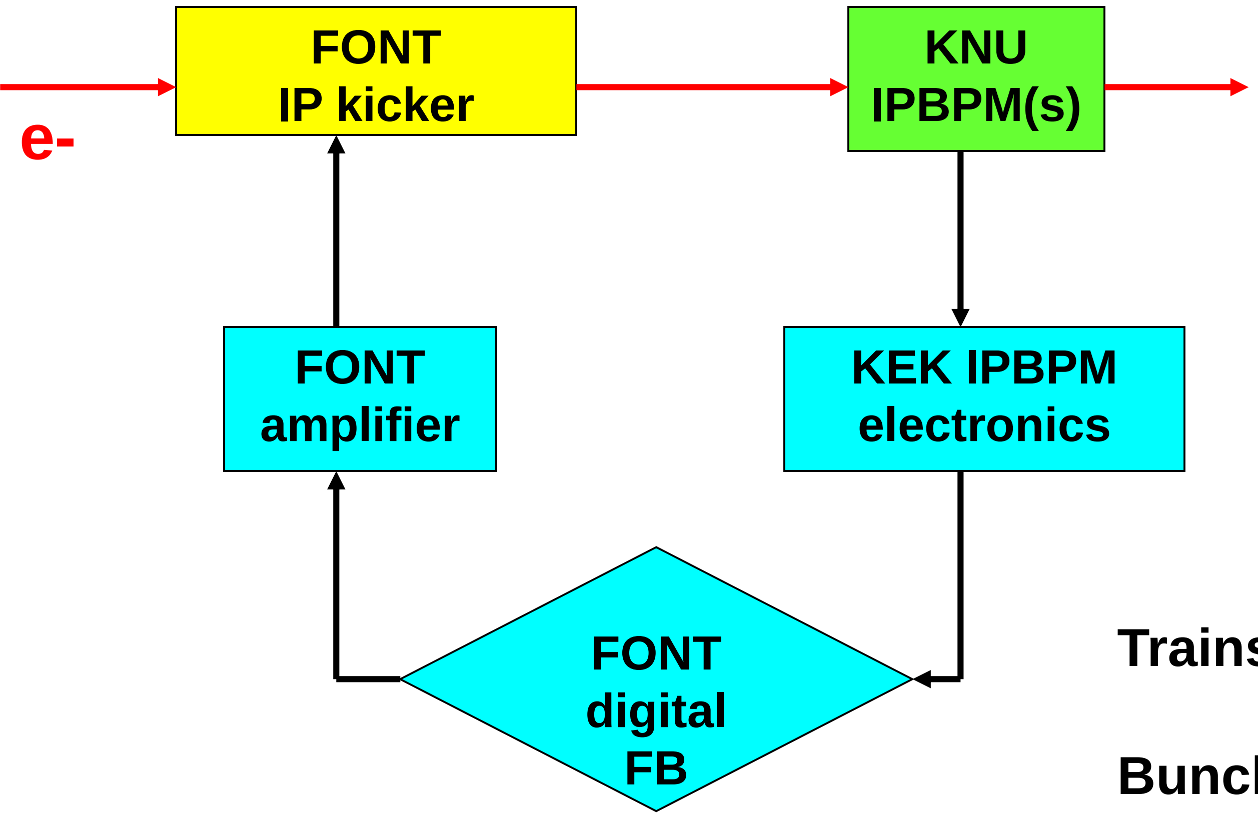
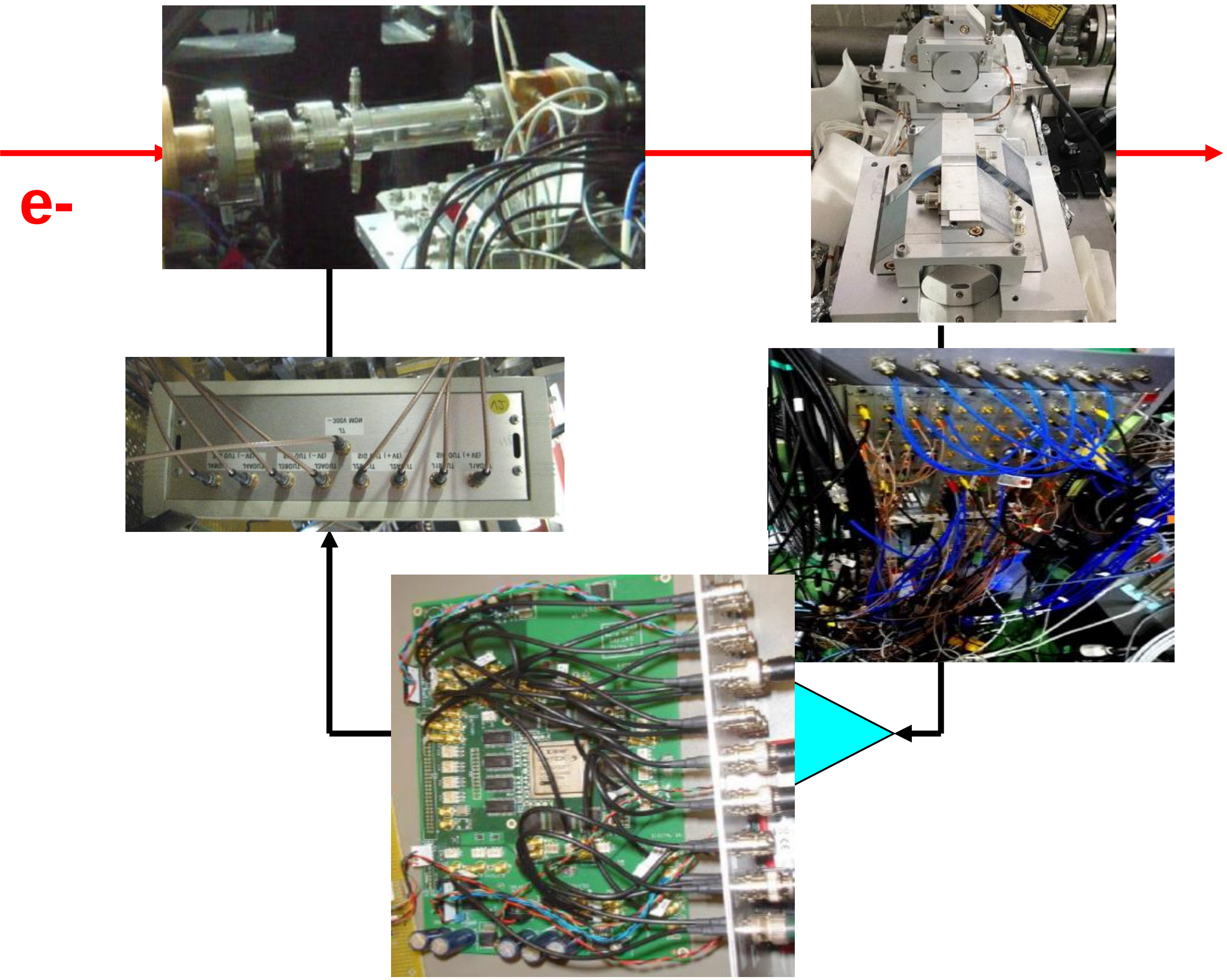


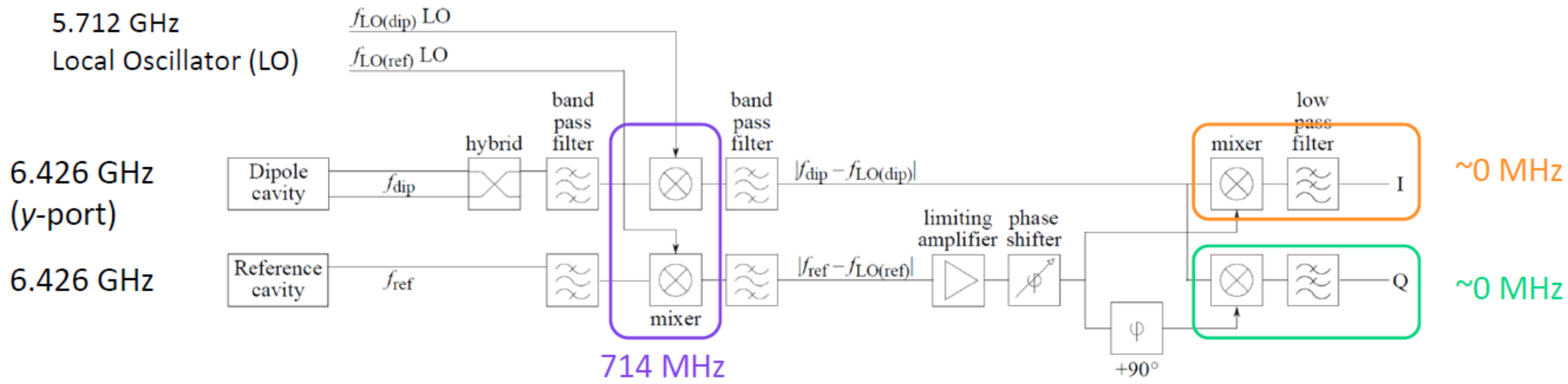
Trains of 2 bunches

Bunch separation c. 280 ns

ATF2 ‘IPFB’ tests



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

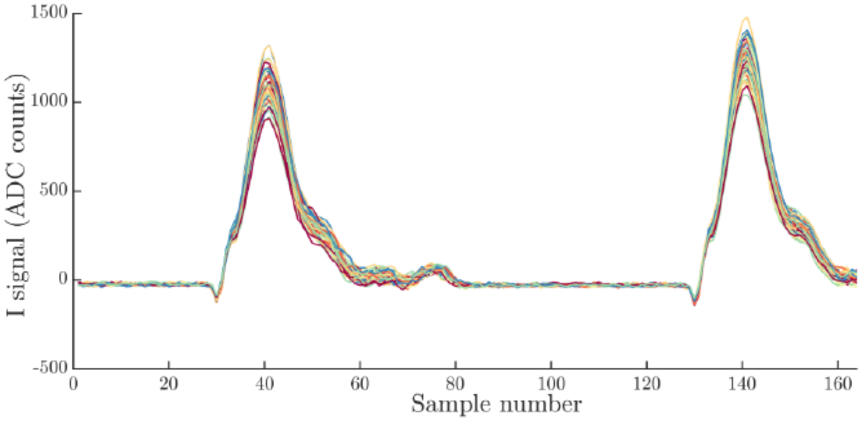
- The waveforms I and Q are digitised at 357 MHz by ADCs on the FONT 5A board; these digitised samples are used to compute a bunch position:

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

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 ~ 300ns

- **Standard version uses single sample from 1 BPM as input**
- **Upgraded (2017/18) to allow:**

  Real-time integration of arbitrary # samples in BPM waveforms

  Input to FB loop from multiple BPMs

  → improved position resolution in real time

  → better FB stabilisation of beam

  Latency measured ~ 232 ns

Beam stabilisation results (April 2018)

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

Beam stabilisation results (April 2018)

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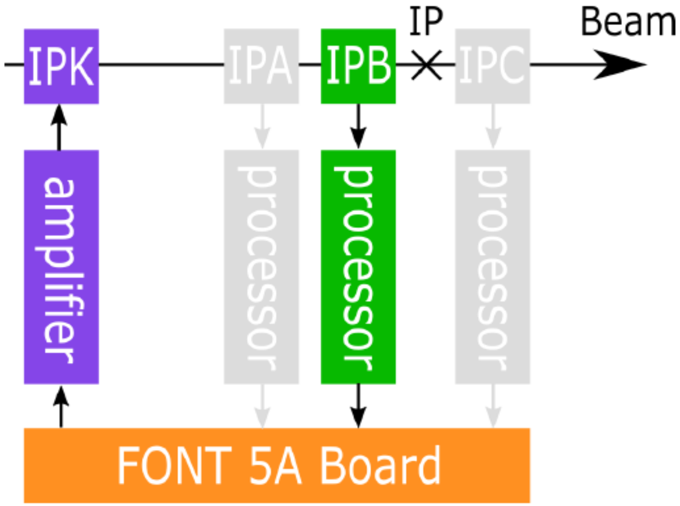
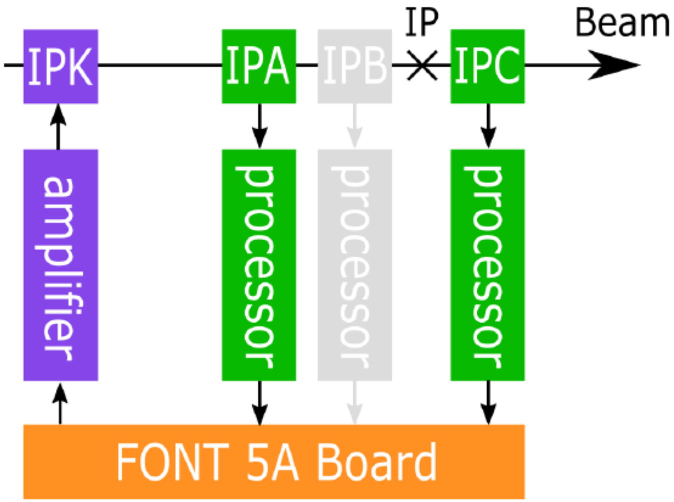


	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	109 ± 11	118 ± 8
2	119 ± 12	50 ± 4



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

Beam stabilisation results (April 2018)

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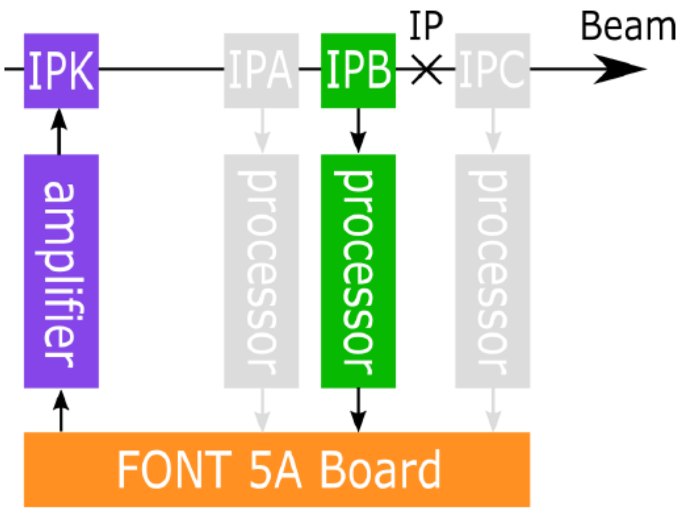

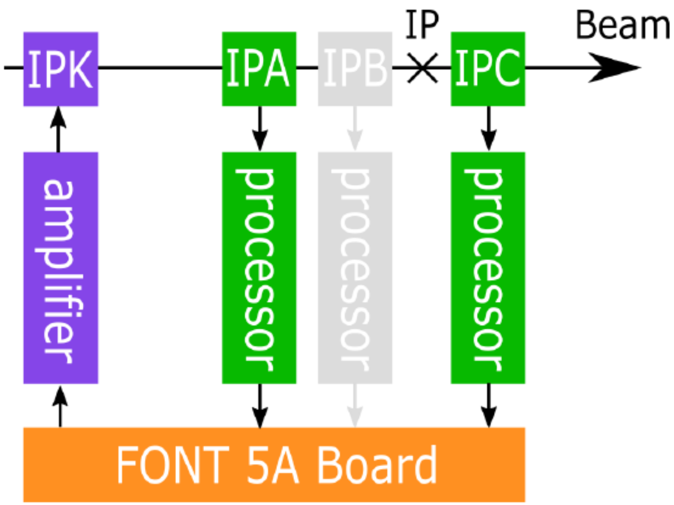

	Position jitter (nm)	
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1	109 ± 11	[illegible]
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	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	106 ± 16	[illegible]
2	96 ± 10	41 ± 4

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

Latest beam stabilisation results from ATF2

- Succeeded in obtaining real-time beam position determination with a resolution of 20 nm
- Extremely promising for CLIC BDS
- Using FB have stabilised beam to c. 40 nm
- Tests will continue Autumn 2018
- Theoretically possible to reach 25 nm stabilisation

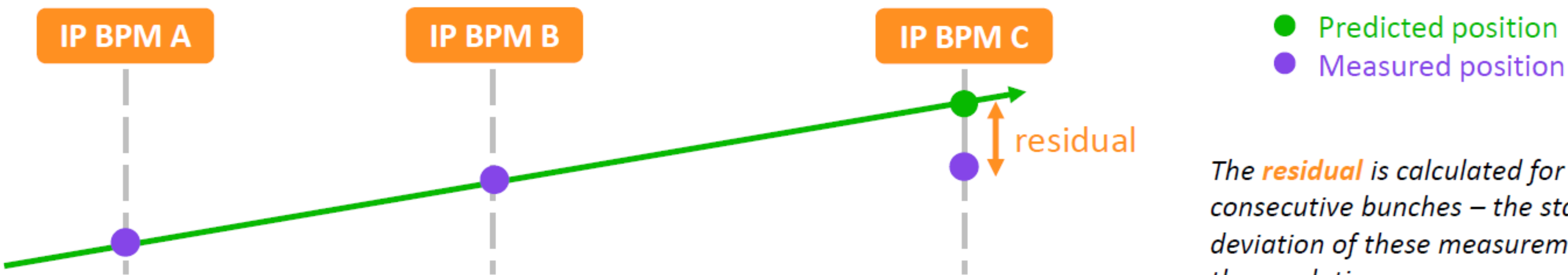
thanks for your attention!

Extra material

Calculating the Resolution

- Only two BPMs are required to characterise the straight-line bunch trajectory, so we are able to use the third BPM to estimate the resolution of the measurement.
- The resolution which is relevant for feedback is the **geometric resolution** – determined using the longitudinal separation of the BPMs. We can achieve better resolution measurements in off-line analysis by using **least squares fitting** for the bunch position but this is not possible within the latency required for feedback

$$\text{residual} = y_{\text{pred}} - y_{\text{meas}}$$
$$\text{resolution} = \text{std}(\text{residuals})$$



*The **residual** is calculated for many consecutive bunches – the standard deviation of these measurements is the resolution.*

Resolution Results

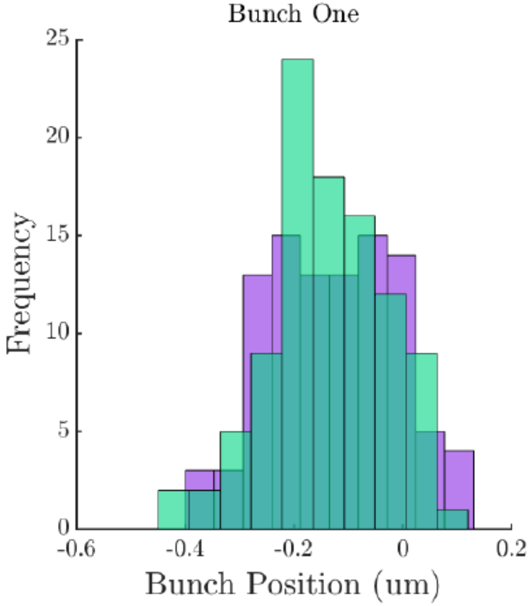
- Resolution results from April 2018: we were able to achieve resolution of ~20 nm, and we were able to reproduce this performance consistently across ten repeat data sets, with all ten data sets having sub-25 nm resolution.
- There is very little improvement to the resolution from using fitting to position or charge, suggesting the calibration and charge normalisation were performed successfully.
- These data were analysed using an integration window of 15 samples. Single sample resolutions were measured between 40-45 nm.

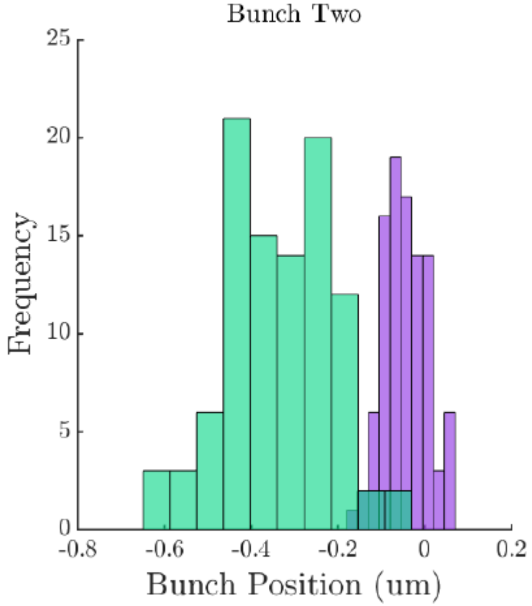
Resolution results from a data set collected 19th April 2018 as part of 10 repeat resolution measurements.

Resolution	IPA (nm)	IPB (nm)	IPC (nm)	Comments
Geometric	20.6 ± 1.0	20.6 ± 1.0	20.6 ± 1.0	Resolution achievable for feedback
Fitting position	20.4 ± 1.0	20.5 ± 0.8	20.3 ± 0.8	Fit out inaccuracies in calibration
Fitting position and charge	19.9 ± 0.9	19.9 ± 0.8	19.7 ± 0.9	Fit out inaccuracies in calibration and position-charge correlation (from imperfect charge normalisation)

1-BPM Feedback Results – With Integration

Best results demonstrated for 1-BPM feedback mode with stabilisation at IPC.





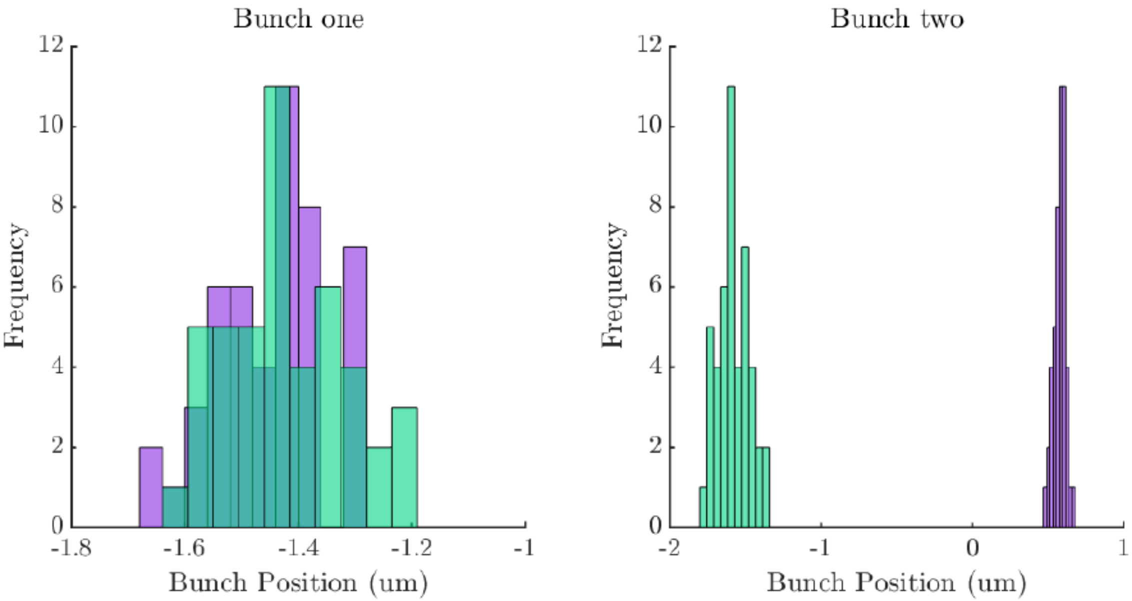
	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	109 ± 11	118 ± 8
2	119 ± 12	50 ± 4

Feedback **off** correlation: **84%**
Feedback **on** correlation: **−26%**

- 10 samples integrated for feedback - optimised empirically.
- Feedback gain: G = 0.95.
- Predicted stabilisation: 65 nm, suggests the measured correlation was lower than the true correlation – typically due to the resolution introducing a random component to the position measurement.
- Stabilisation below 55 nm was reproducible.

2-BPM Feedback Results

Best results demonstrated for 2-BPM feedback mode, with stabilisation at IPB.



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

- Five-sample integration window, empirically optimised to improve both the measured correlation and resolution.
- Feedback stabilising to: **41 ± 4 nm,** shows excellent agreement with predicted stabilisation of 40 nm.
- Feedback gain: G= 0.8.

Feedback off correlation: **92%**

Feedback on correlation: **41%**

The correlation is not fully removed, suggesting feedback gains were set too low; higher gains may offer better performance.

Latency

- Time of flight kicker – BPM: 12ns
- Signal return time BPM – kicker: 32ns

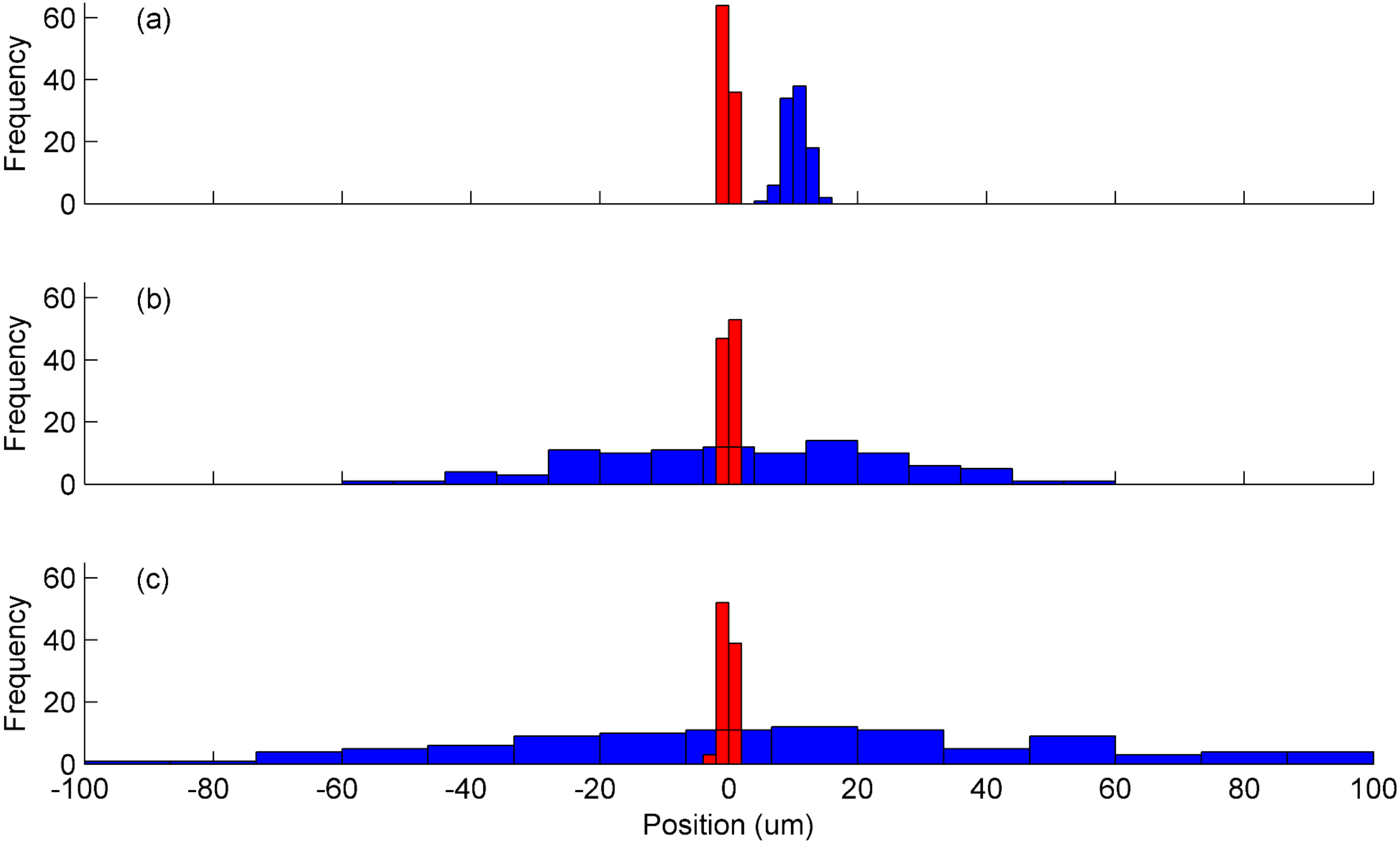
  Irreducible latency: 44ns

- BPM processor: 10ns
- ADC/DAC (4.5 357 MHz cycles) 14ns
- Signal processing (8 357 MHz cycles) 22ns
- FPGA i/o 3ns
- Amplifier 35ns
- Kicker fill time 3ns

  Electronics latency: 87ns

- Total latency budget: 131ns

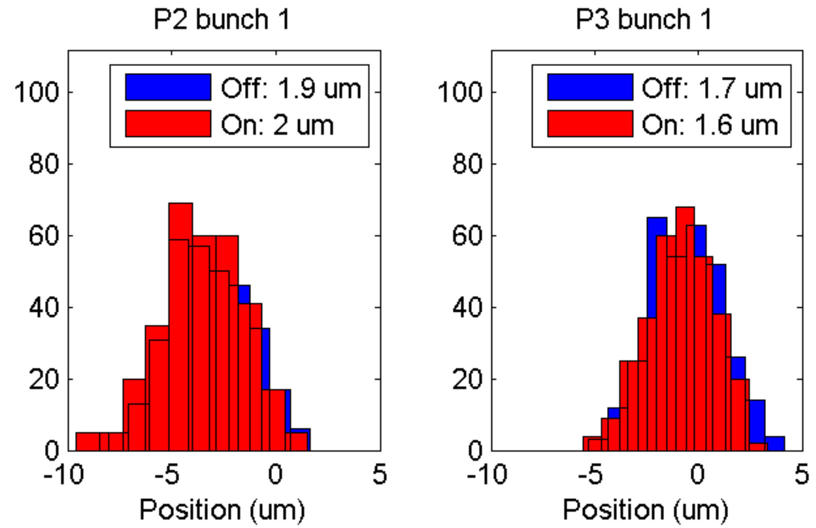
FONT ILC prototype performance



Upstream FB performance

2 bunches separated by 274ns:
measure #1
correct #2

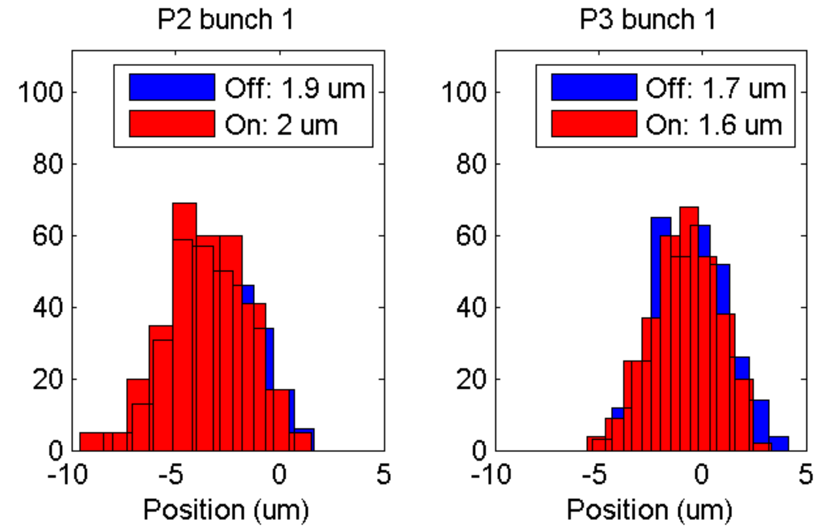
Bunch 1



Upstream FB performance

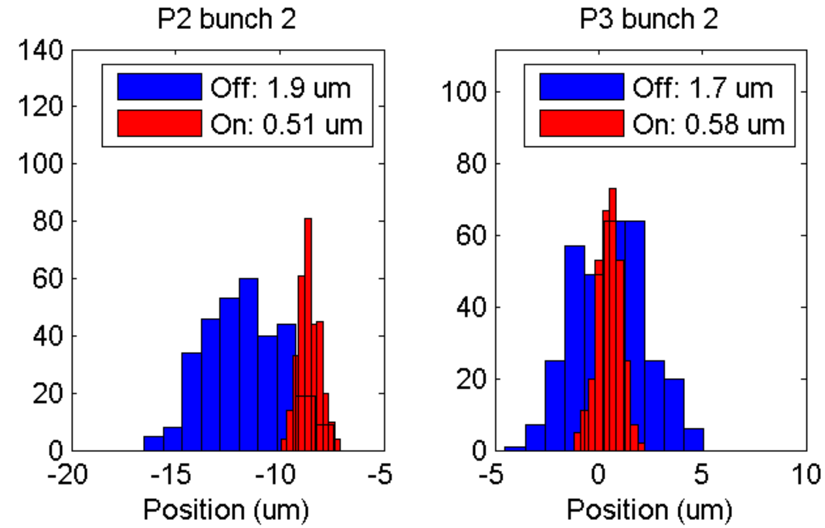
2 bunches separated by 274ns:
measure #1
correct #2

Bunch 1



Bunch 2 corrected to c. 0.5um (resolution limit)

Bunch 2



Upstream FB performance

Witness BPM c. 30m downstream

Beam correction preserved