Progress towards nanometre beam stabilisation at ATF2

Feedback On Nanosecond Timescales (FONT)

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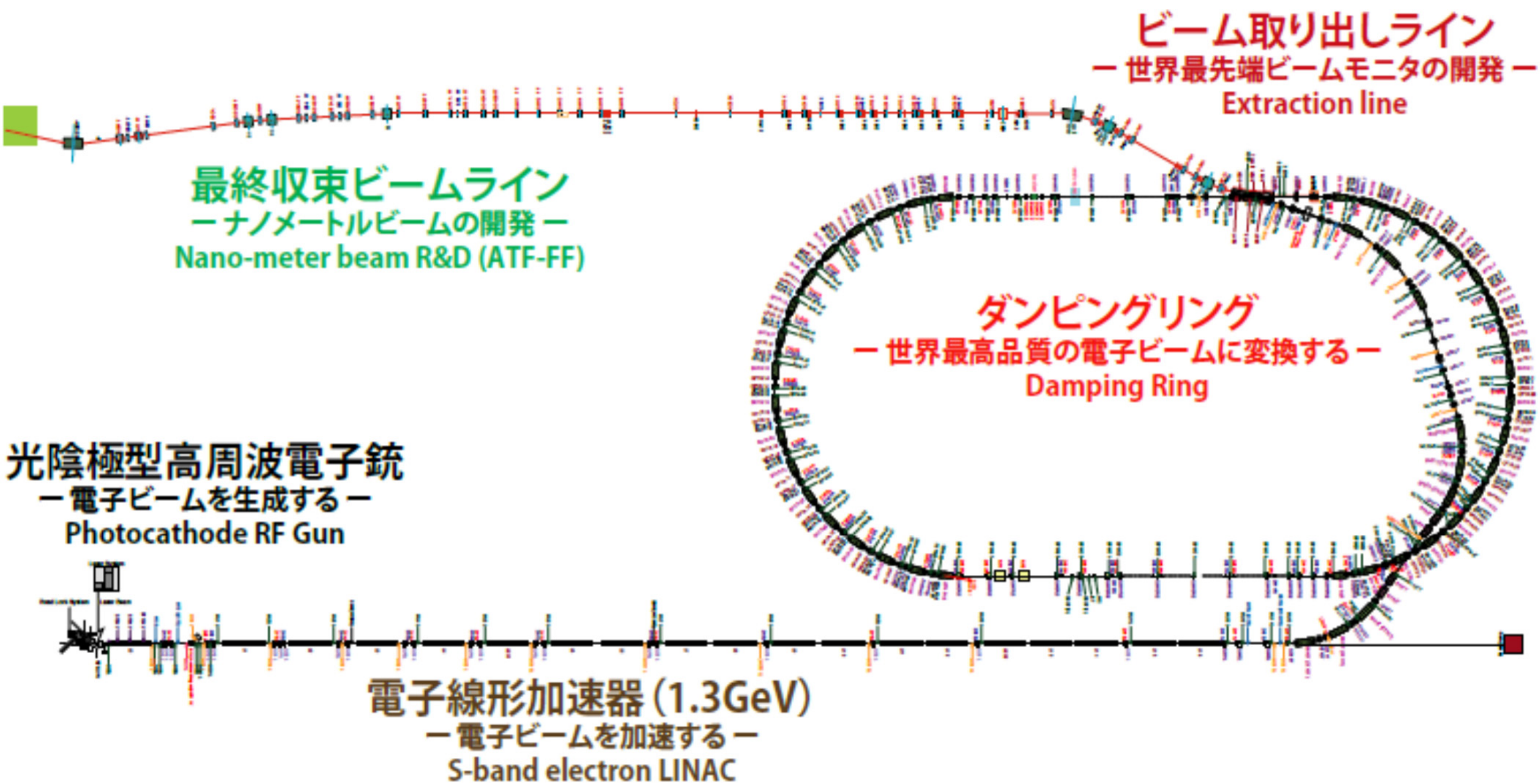
Now at: *CERN; **UBS

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


ビーム取り出しライン
ー 世界最先端ビームモニタの開発 ー
Extraction line
最終収束ビームライン
ー ナノメートルビームの開発 ー
Nano-meter beam R&D (ATF-FF)
ダンピングリング
ー 世界最高品質の電子ビームに変換する ー
Damping Ring
光陰極型高周波電子銃
ー 電子ビームを生成する ー
Photocathode RF Gun
電子線形加速器 (1.3GeV)
ー 電子ビームを加速する ー
S-band electron LINAC

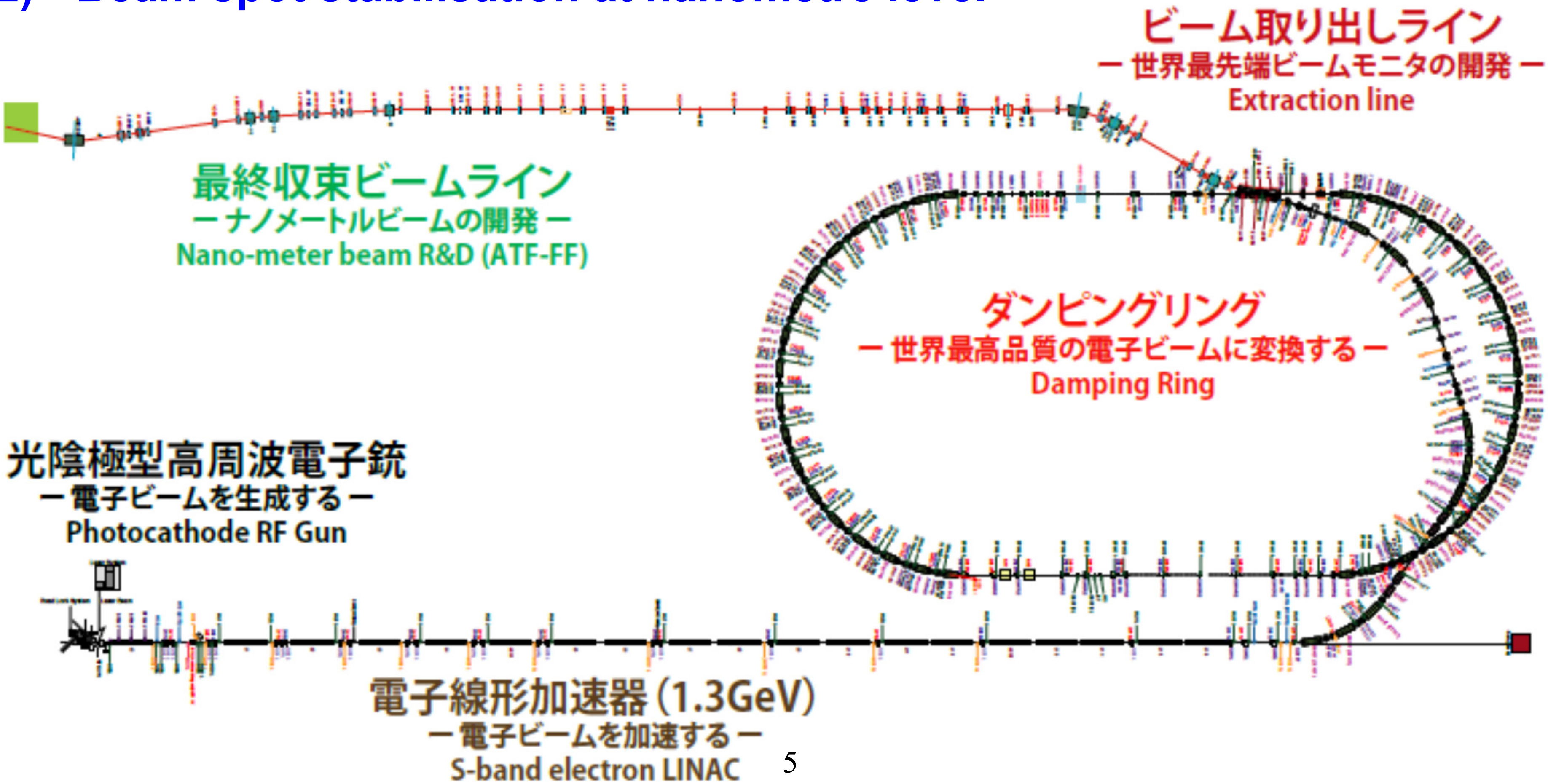
ATF2 design parameters

Parameter			Design value
Energy		(GeV)	1.3
Intensity		(electrons/bunch)	1×10^{10}
Repetition rate		(Hz)	3.12
Horizontal emittance	ϵ_x	(m rad)	2×10^{-9}
Vertical emittance	ϵ_y	(m rad)	1.2×10^{-11}
Horizontal IP beam size	$\hat{x}^*$	(m)	2.8×10^{-6}
Vertical IP beam size	$\hat{y}^*$	(m)	3.7×10^{-8}
Horizontal IP beta function	β_x^*	(m)	4×10^{-3}
Vertical IP beta function	β_y^*	(m)	1×10^{-4}
RMS energy spread		(%)	0.08

ATF2/KEK: prototype final focus

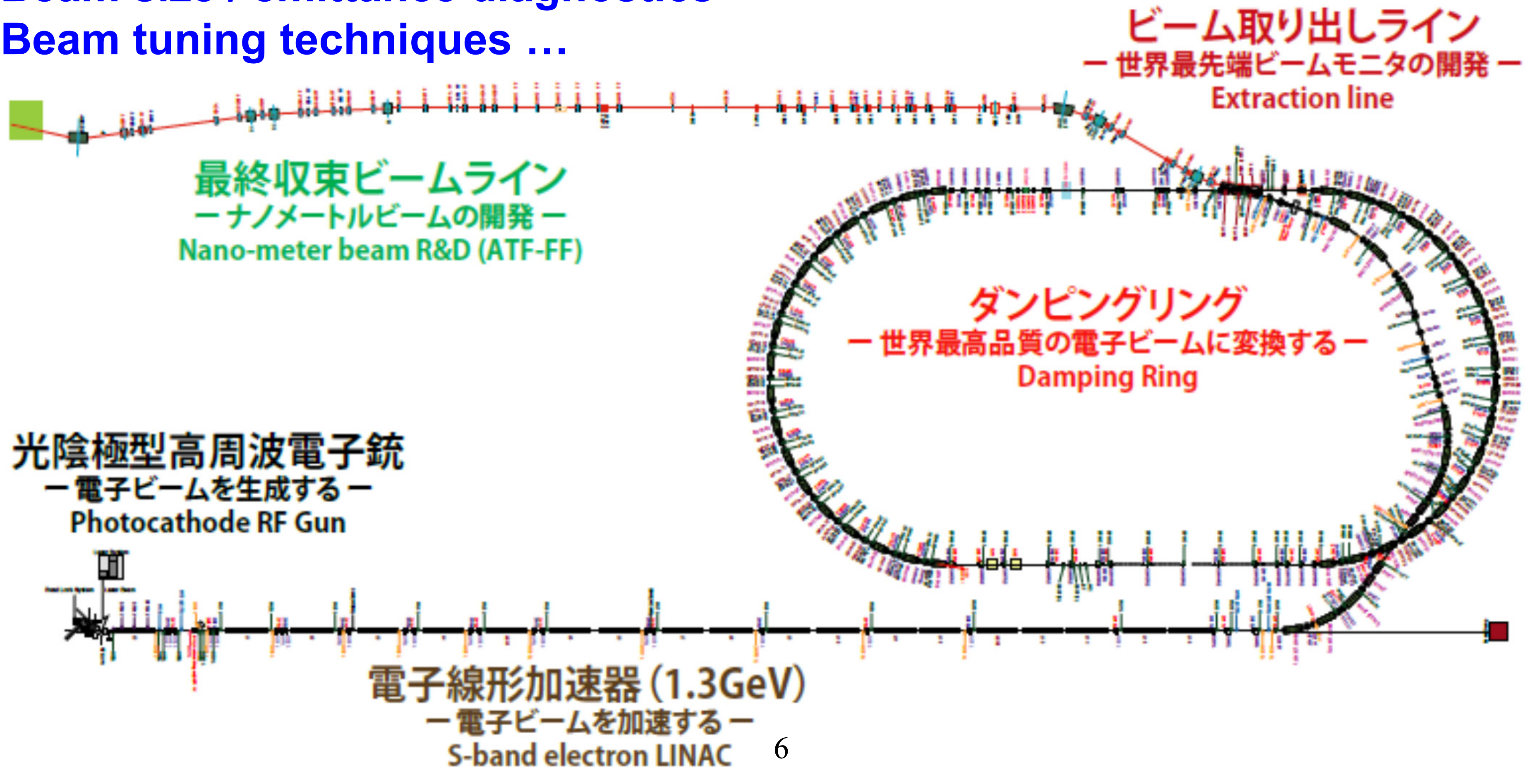
Goals:

1) 37 nm beam spot (44 nm achieved 2014 – reproducibly)
2) Beam spot stabilisation at nanometre level

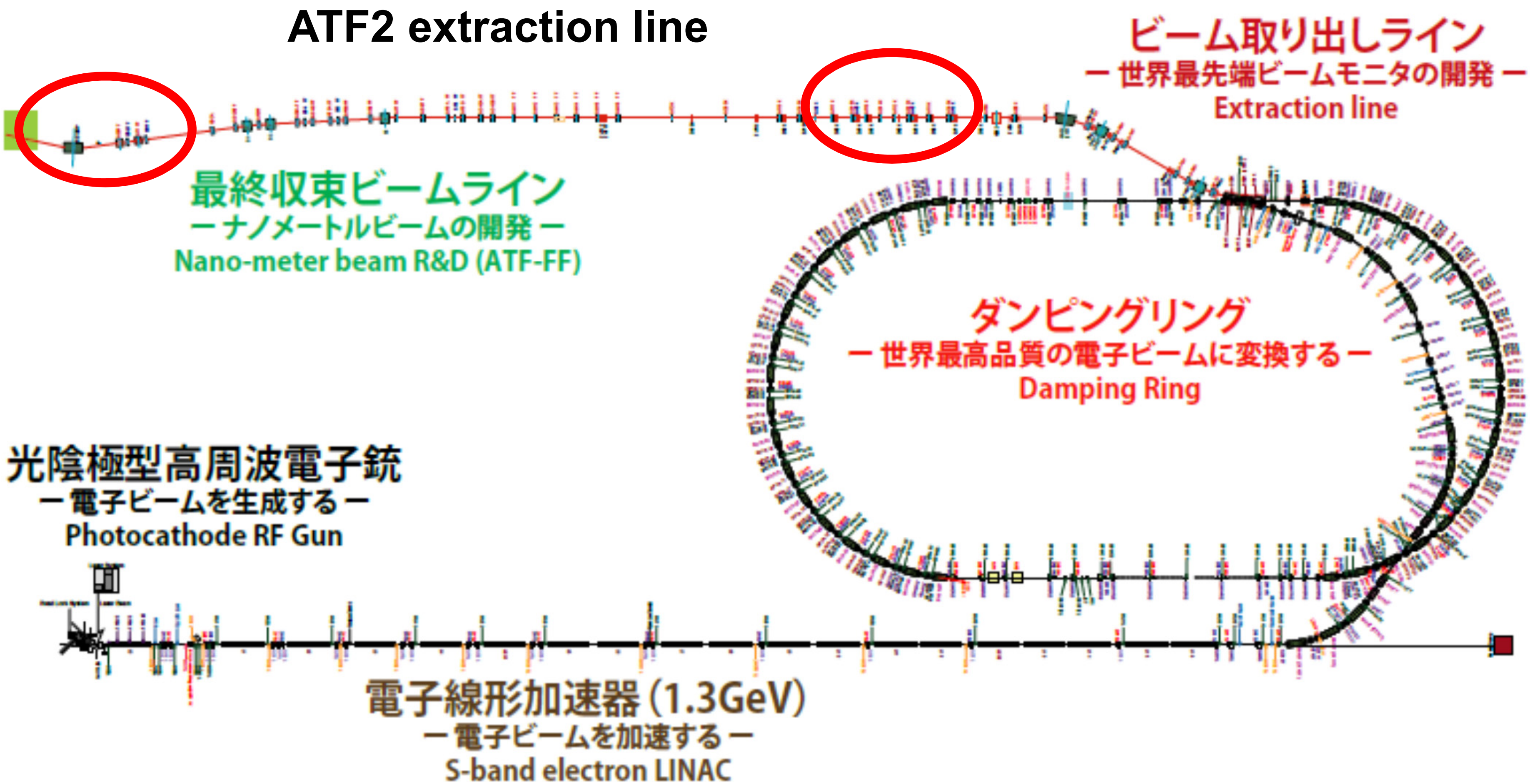


ATF2/KEK: prototype final focus

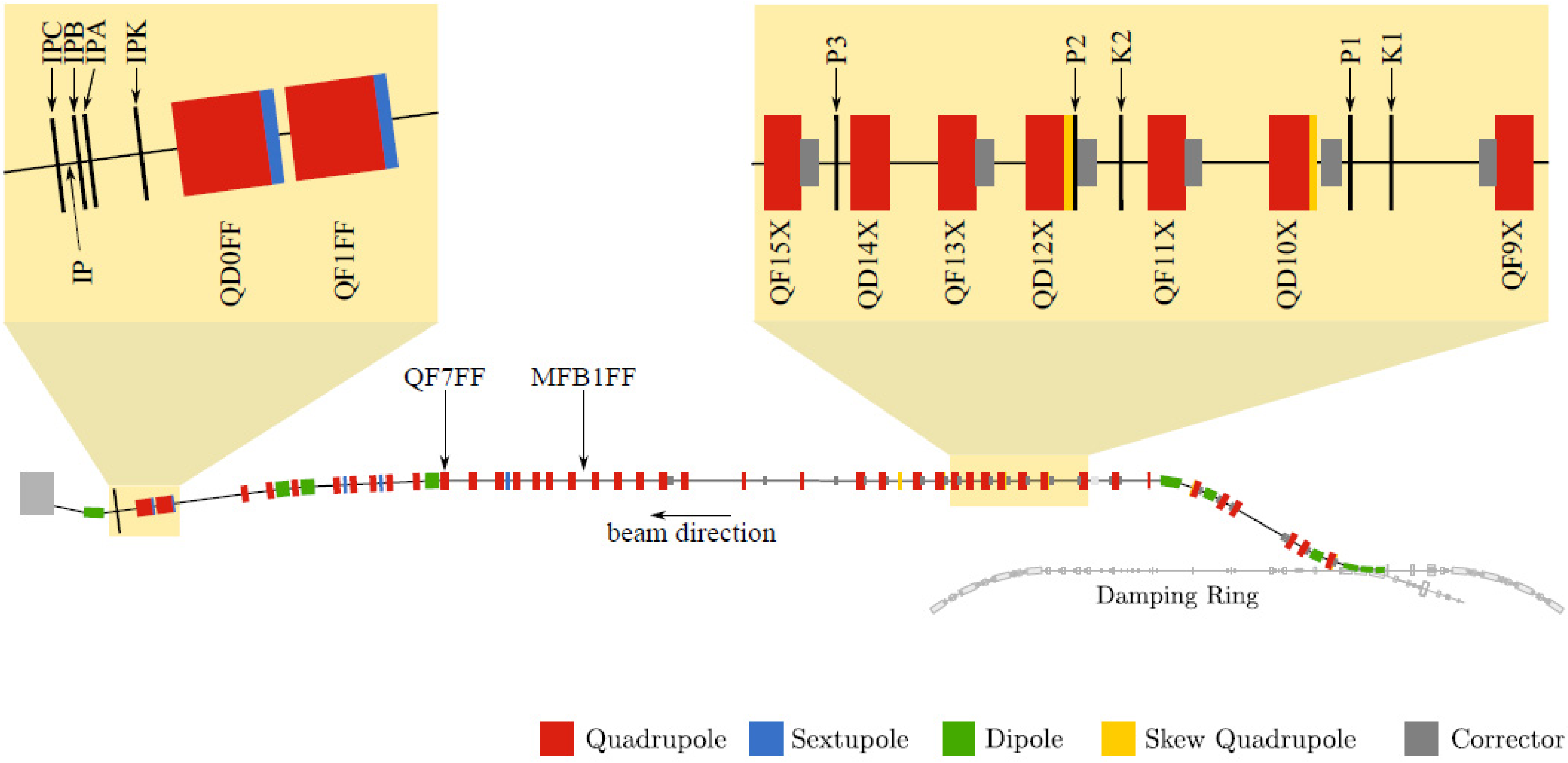
Beam feedback + feed-forward systems
Precision cavity + stripline BPMs
Beam size / emittance diagnostics
Beam tuning techniques …



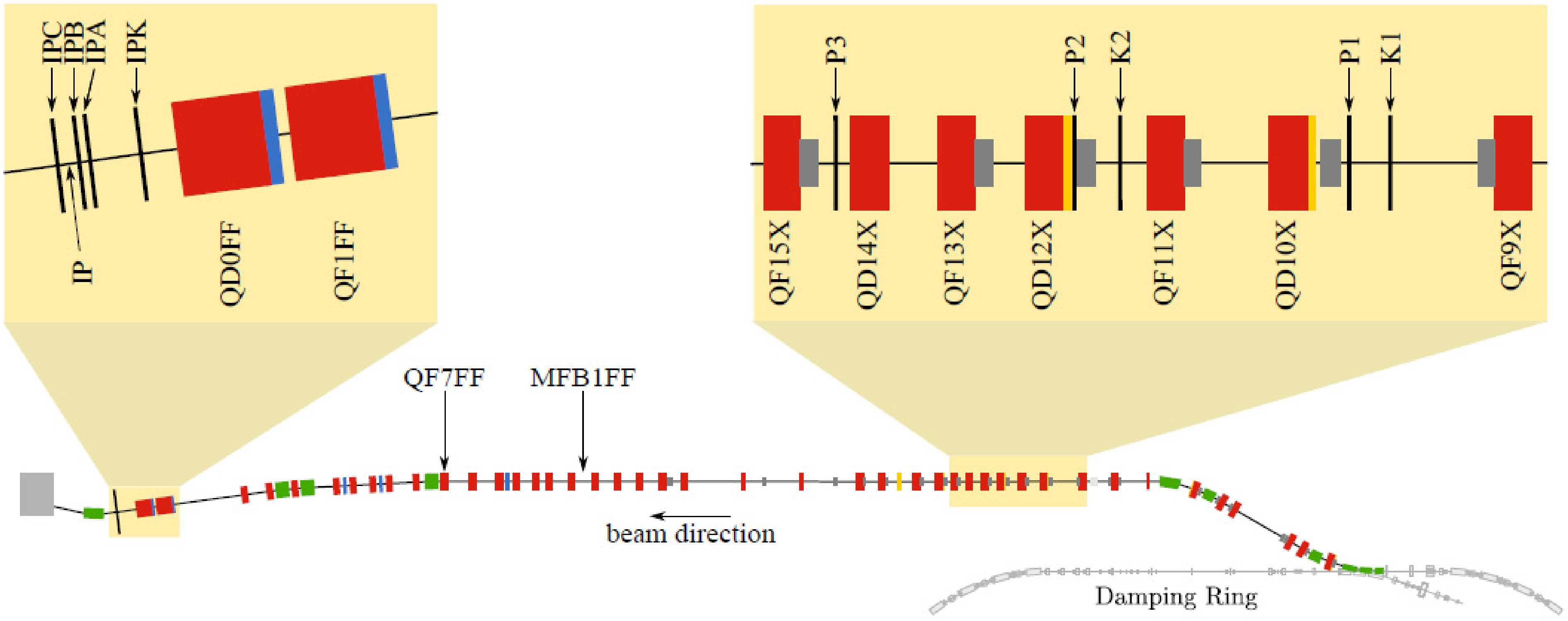
FONT5 ‘intra-train’ feedbacks



FONT5 ‘intra-train’ feedbacks

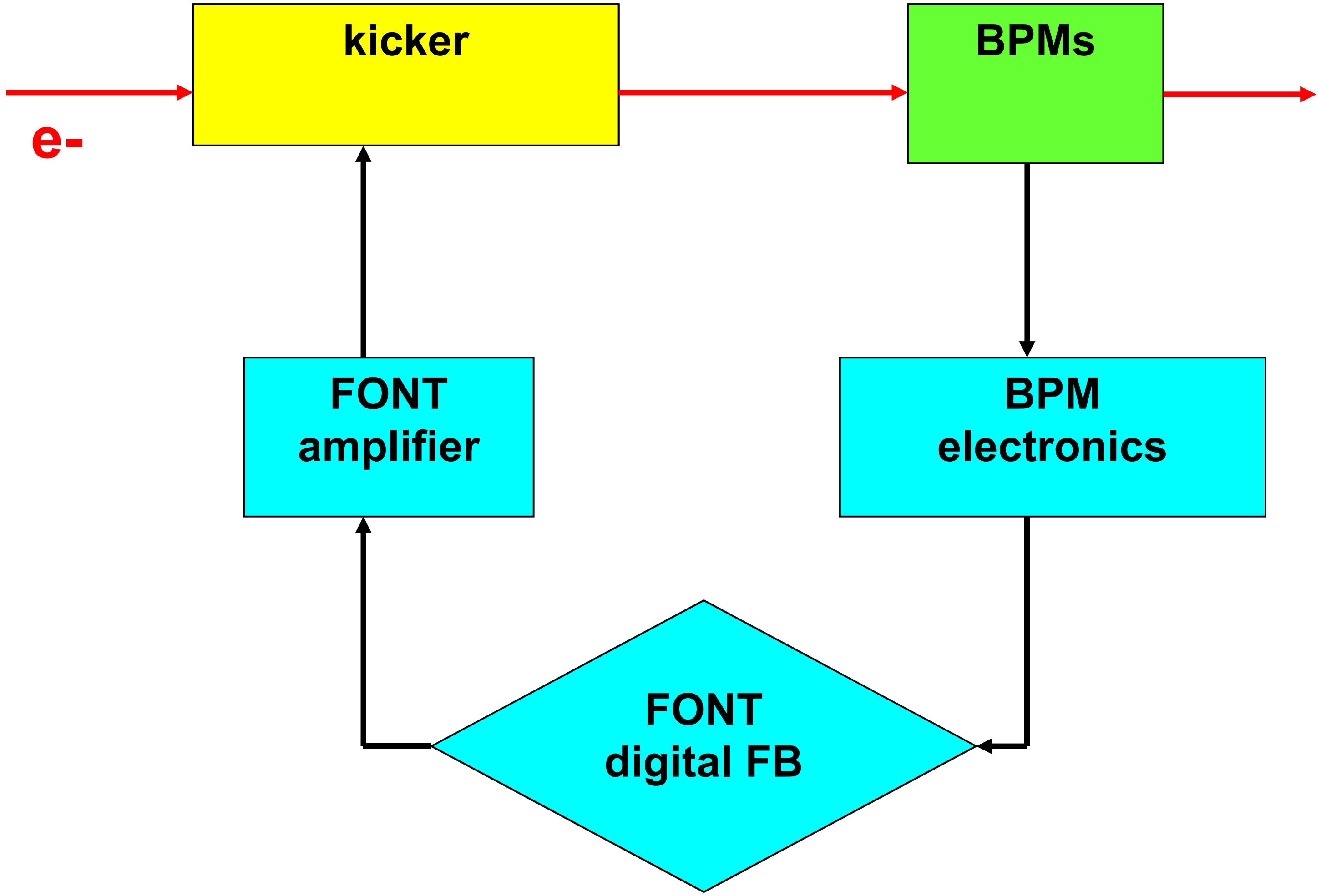


Stabilising beam near IP

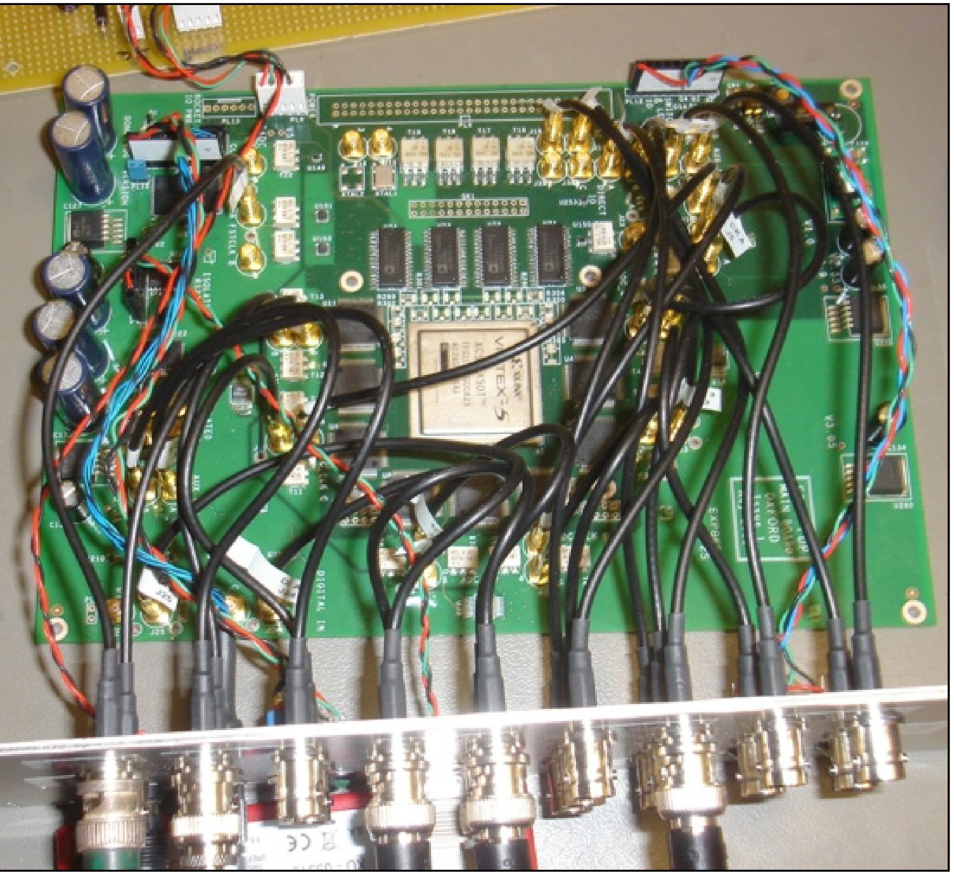


1. **Upstream FB:** monitor beam at IP
2. **Feed-forward:** from upstream BPMs → IP kicker
3. **Local IP FB:** using IPBPM signal and IP kicker

FB loop schematic



FONT5 digital FB board



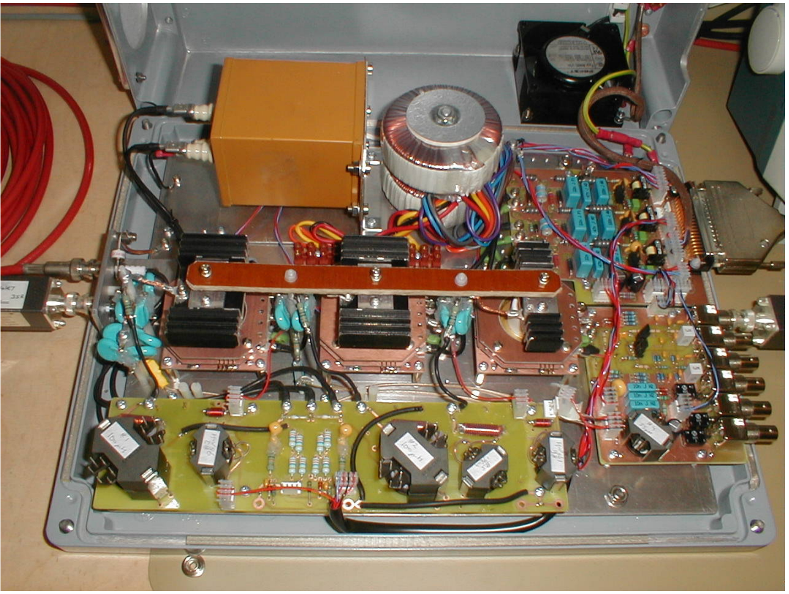
Xilinx Virtex5 FPGA

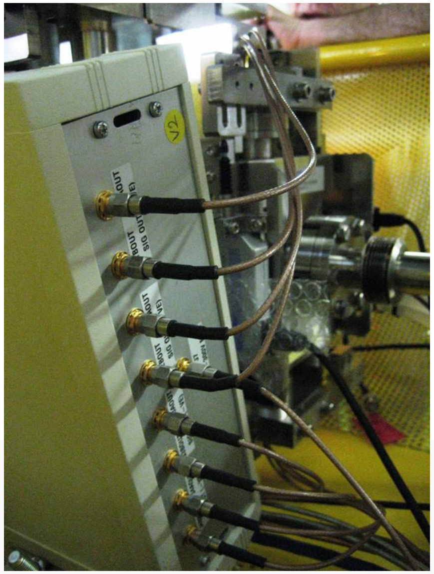
9 ADC input channels (TI ADS5474)

4 DAC output channels (AD9744)

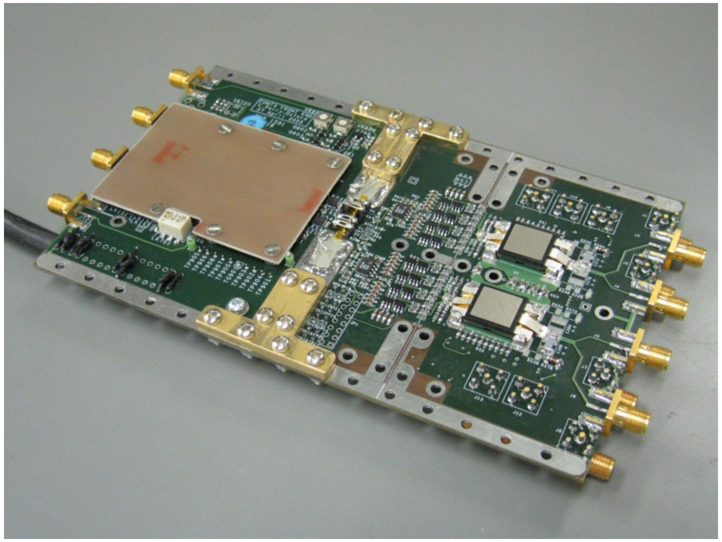
Clocked at up to 400 MHz (phase-locked to beam)

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:

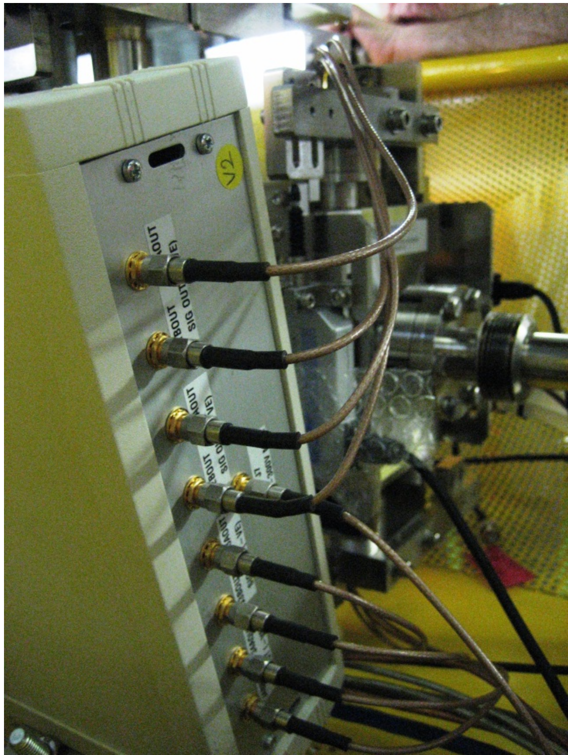
+- 15A (kicker terminated with 50 Ohm)

+- 30A (kicker shorted at far end)

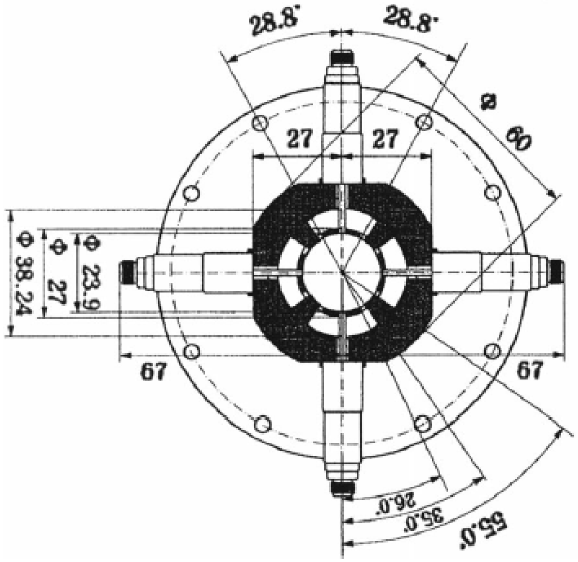
35ns risetime (to 90%)

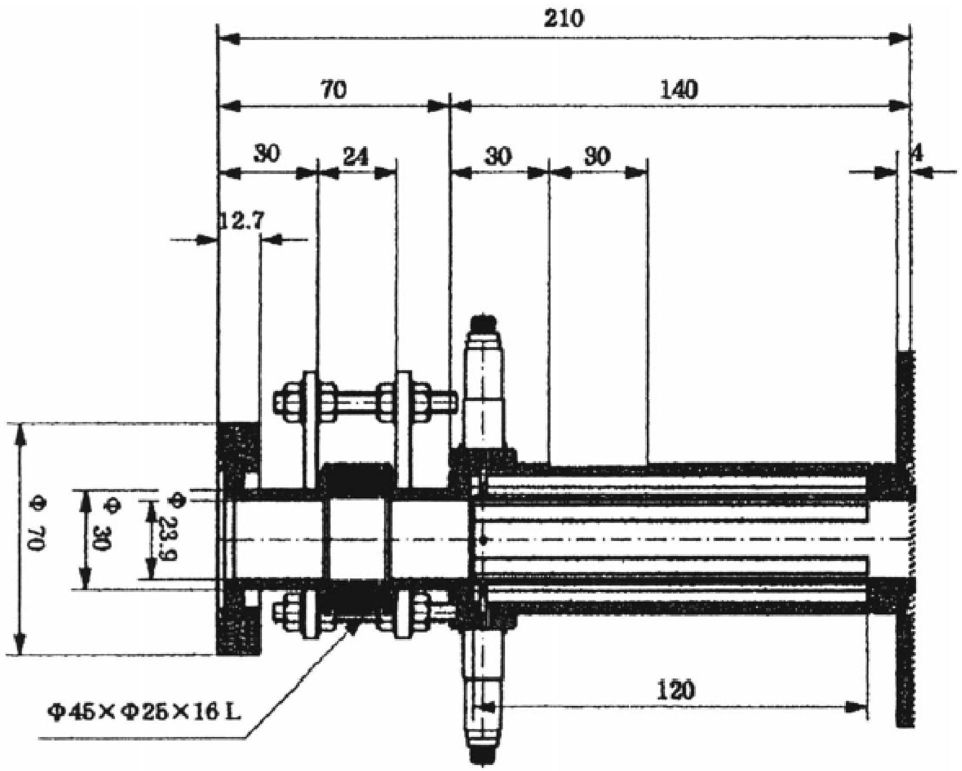
pulse length 10 us

repetition rate 10 Hz

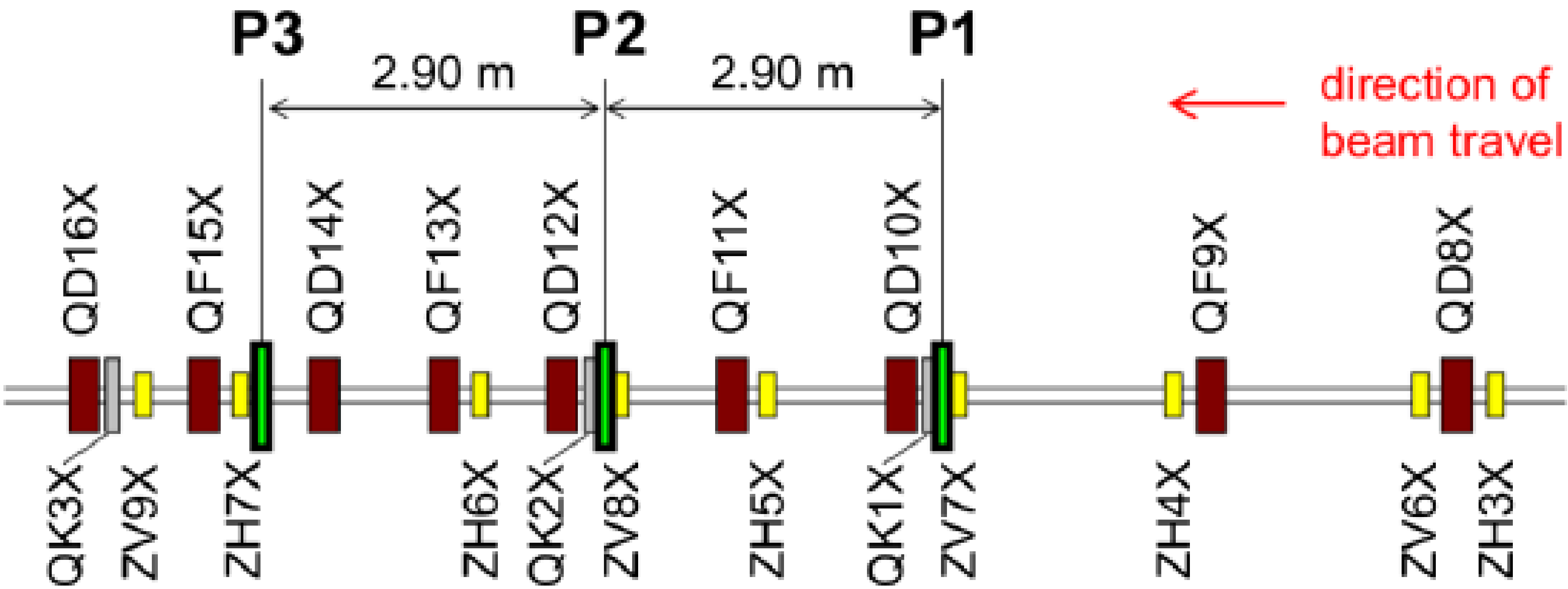


Stripline BPMs





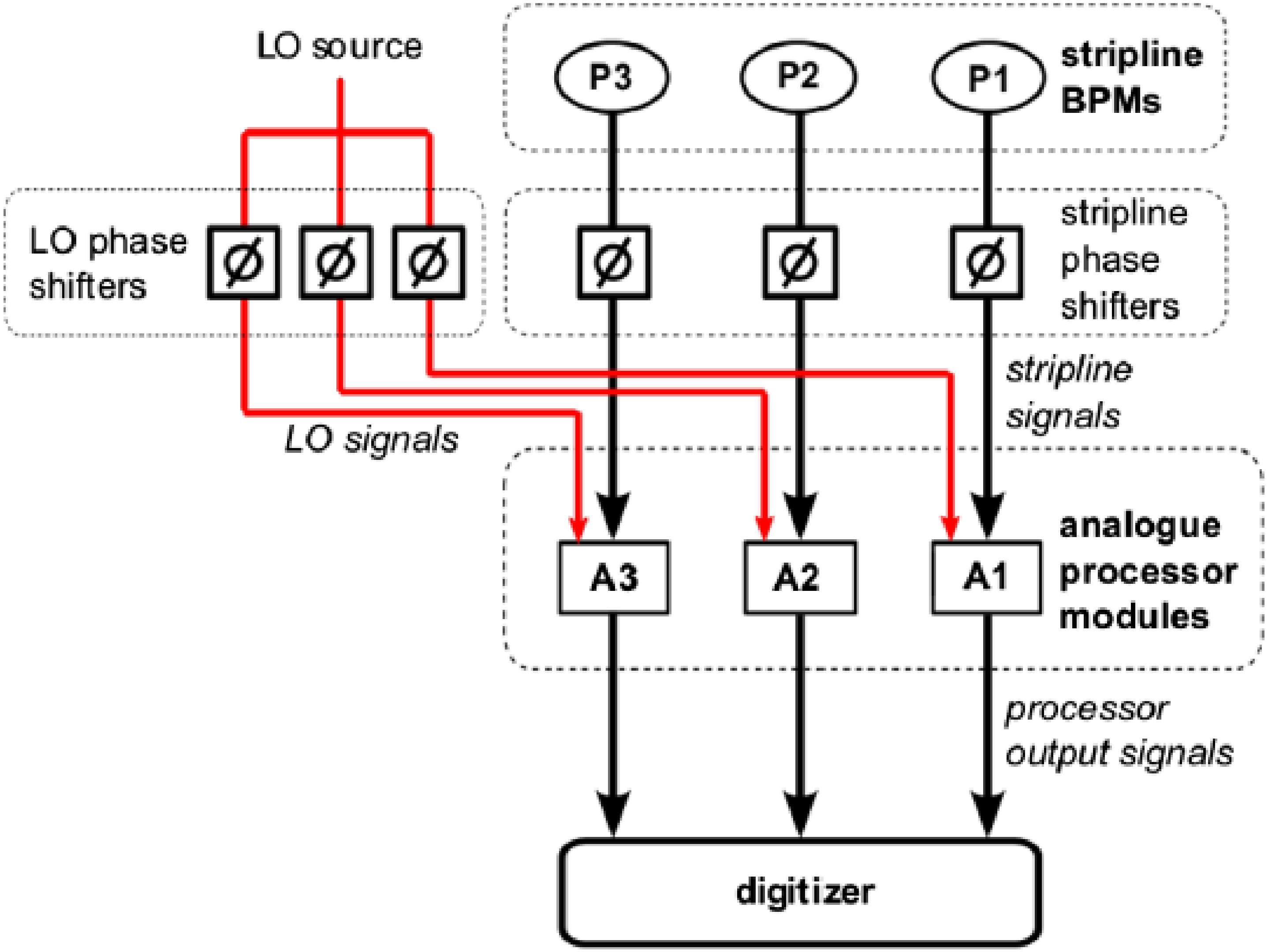
FONT5 stripline BPM system



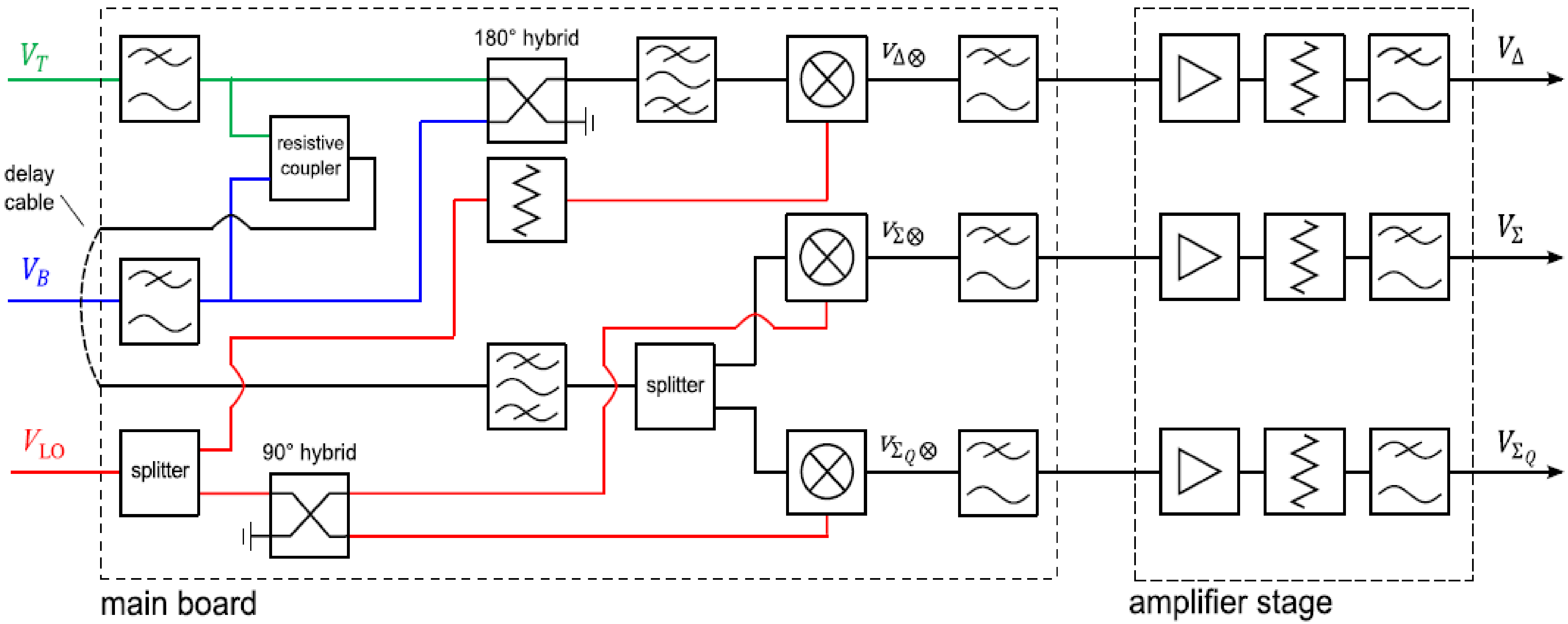
Stripline BPMs

BPM on
x-y mover
system (IFIC)

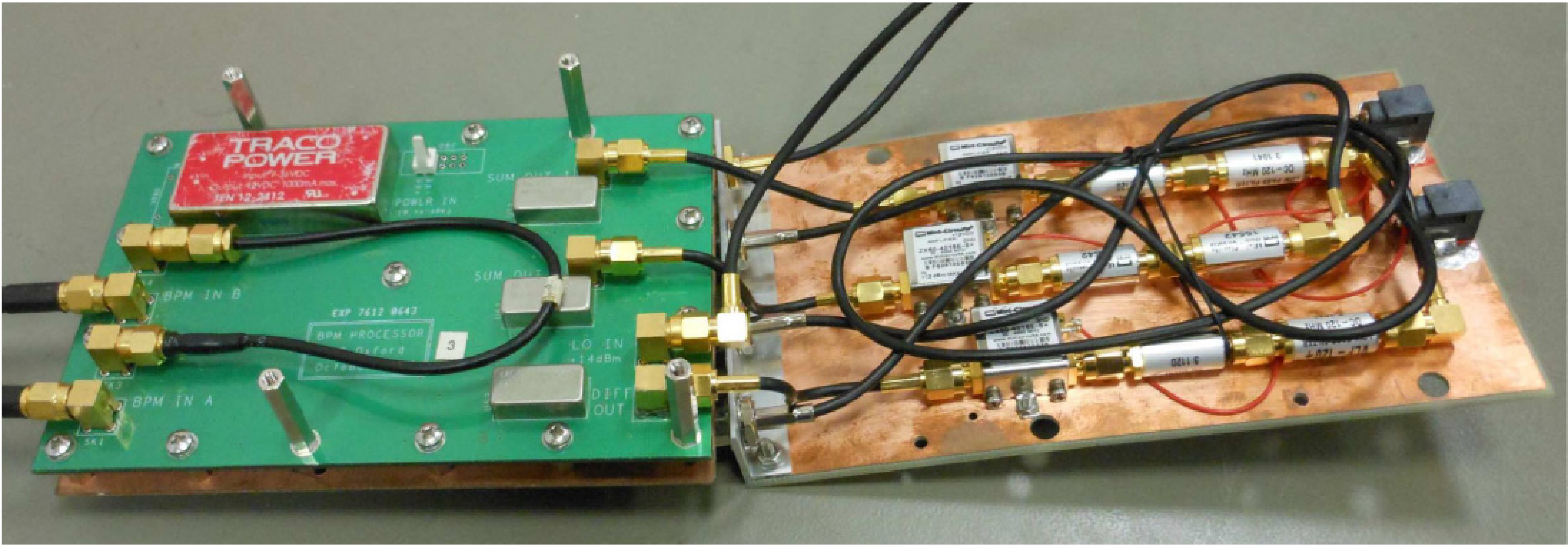
BPM readout


LO source
P3
P2
P1
stripline
BPMs
LO phase
shifters
stripline
phase
shifters
stripline
signals
LO signals
A3
A2
A1
analogue
processor
modules
processor
output signals
digitizer

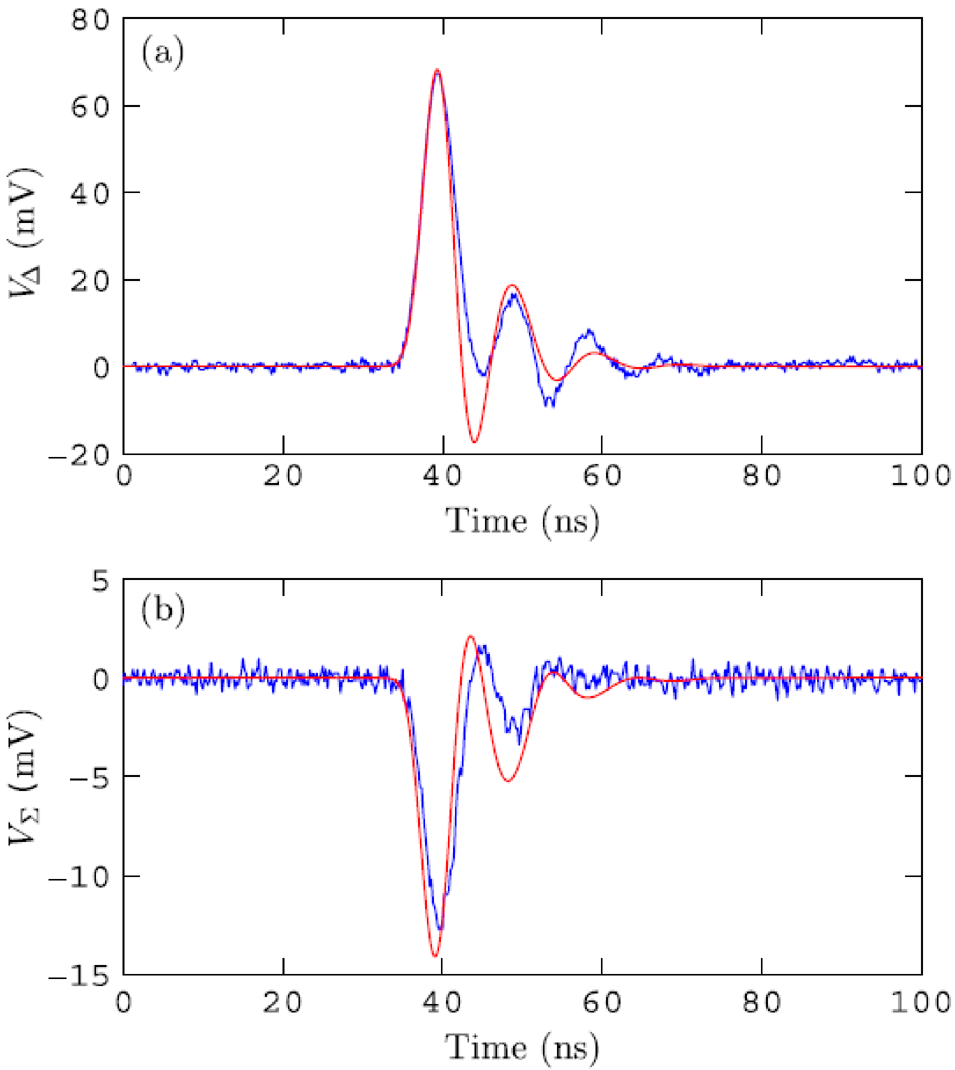
BPM signal processing



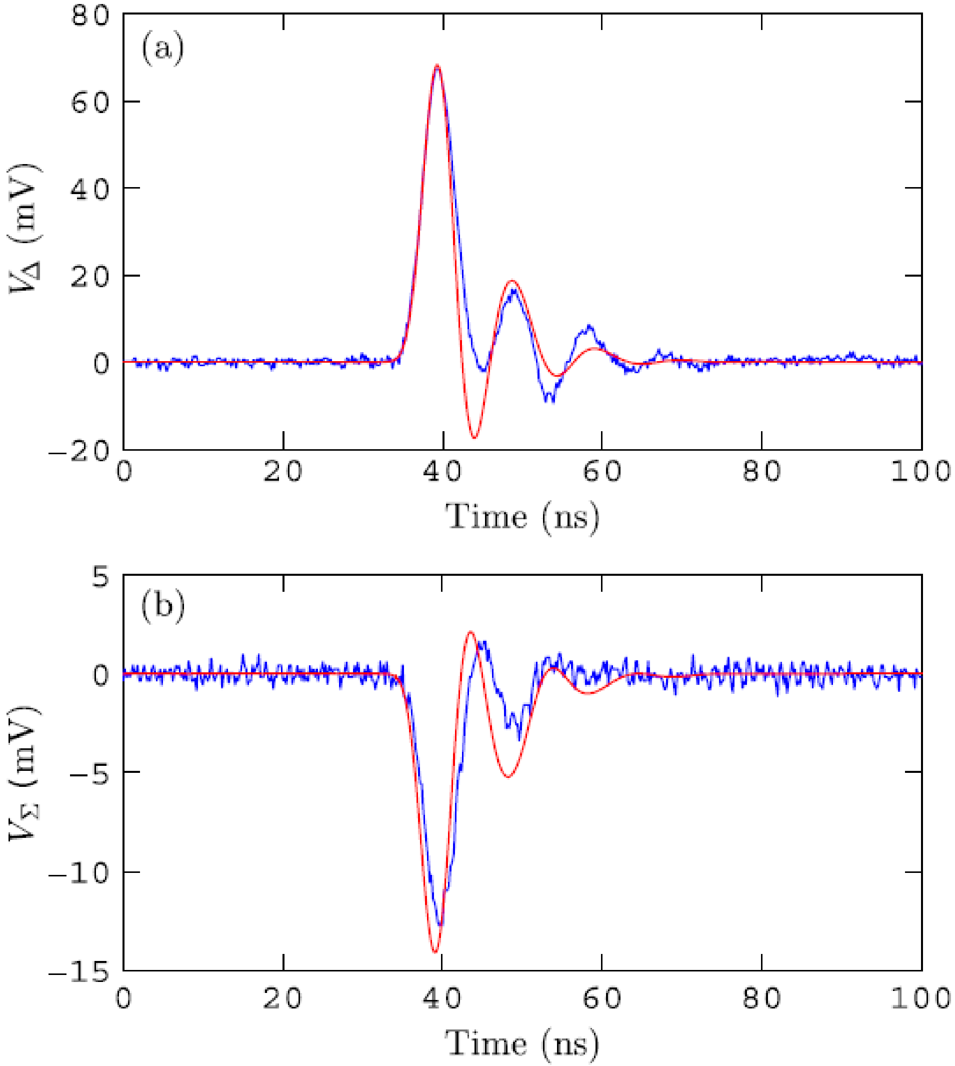
BPM signal processor



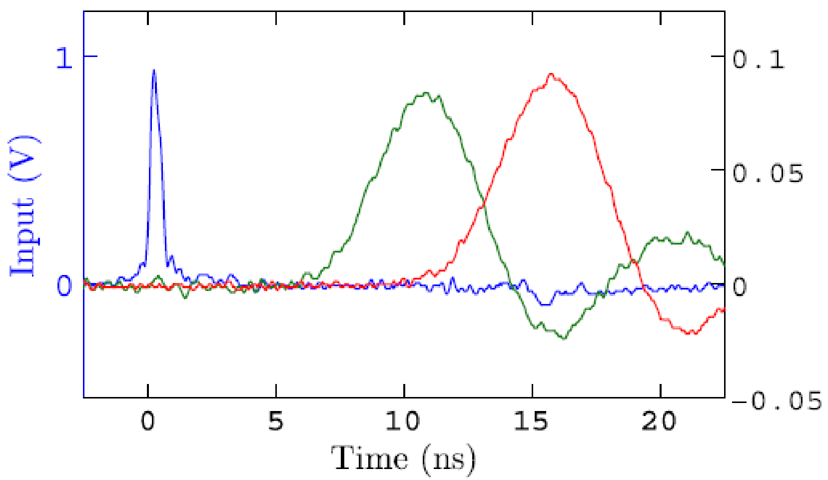
BPM signal processor outputs



BPM signal processor latency

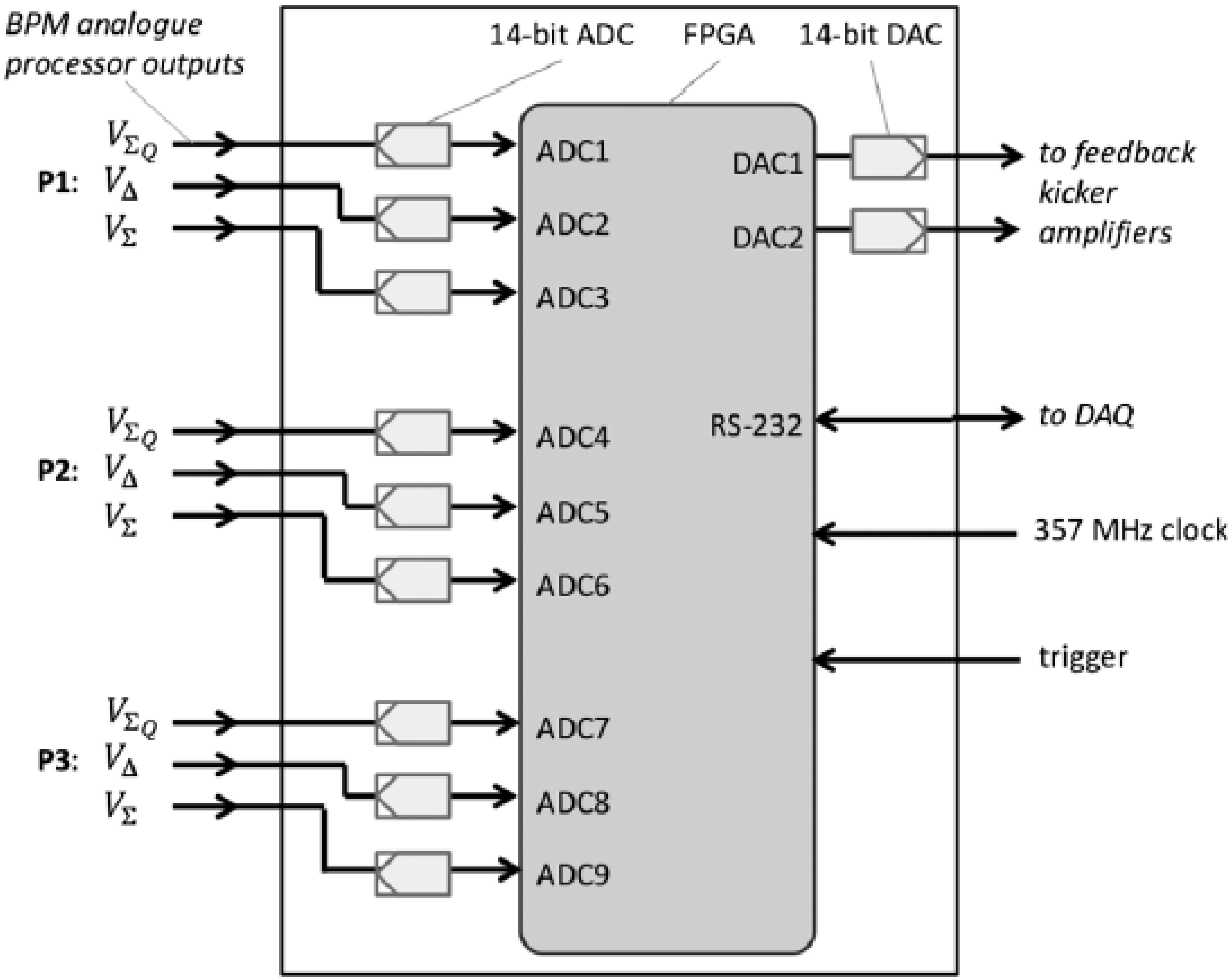


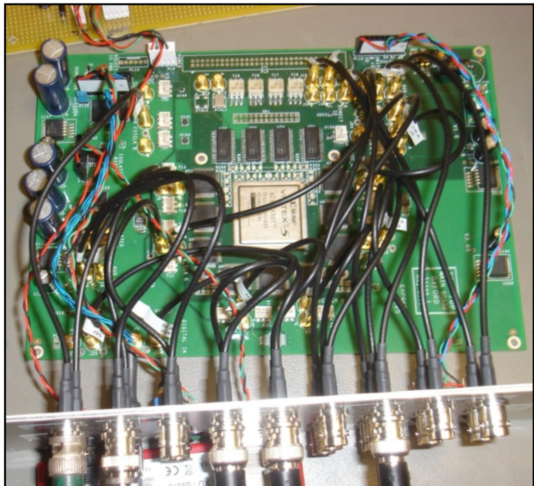
Bench latency meas:



10ns or 15ns with amplifier stage

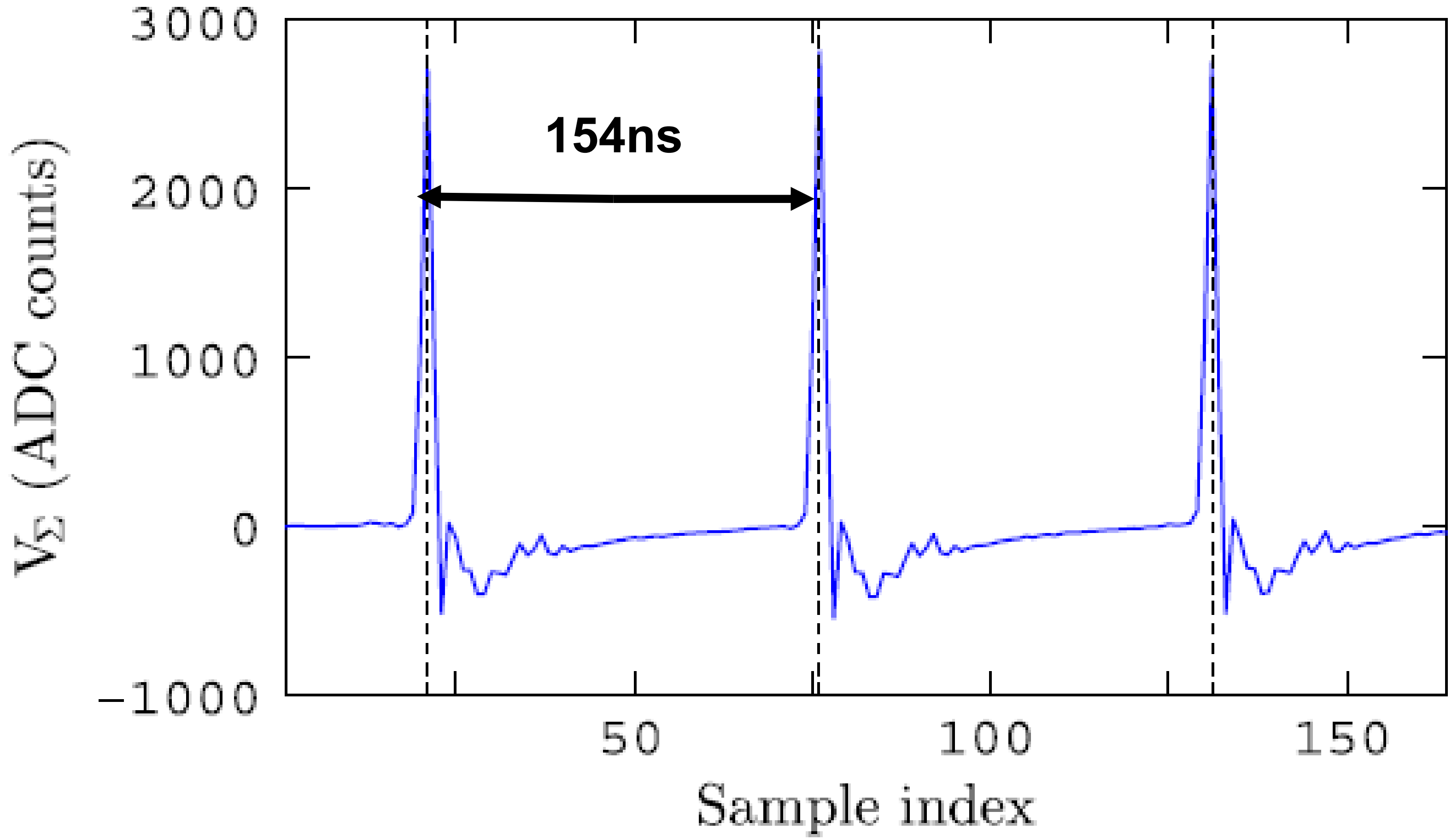
BPM signal digitisation



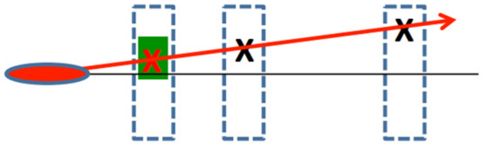


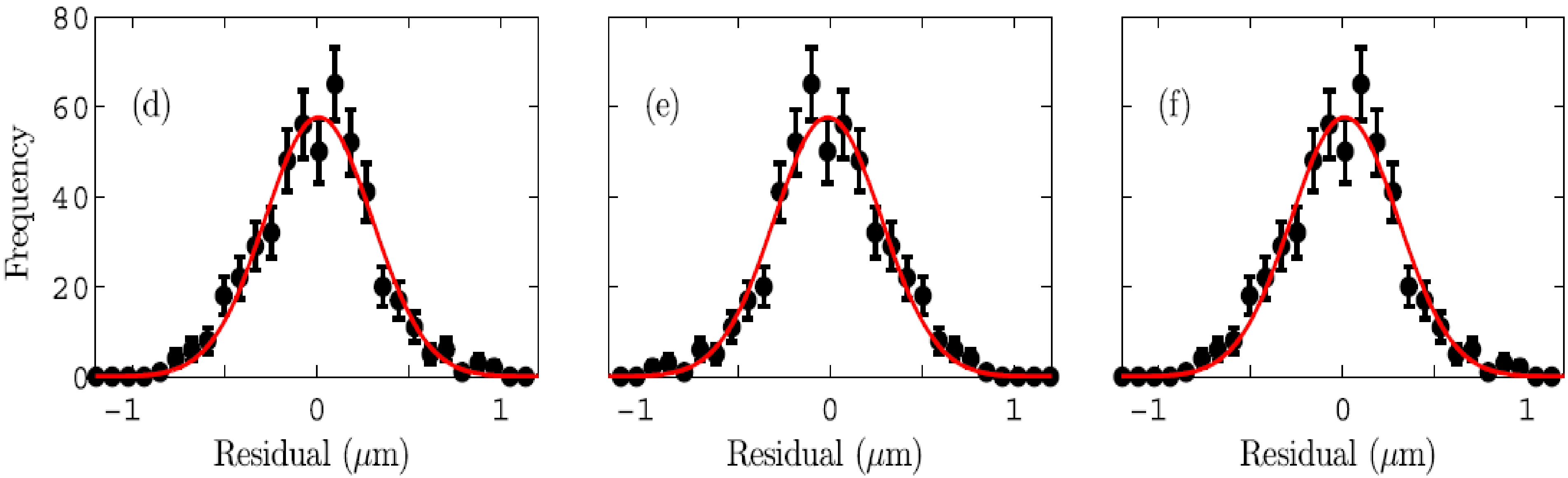
3-bunch train at ATF (proxy for ILC)

Single-shot measurement



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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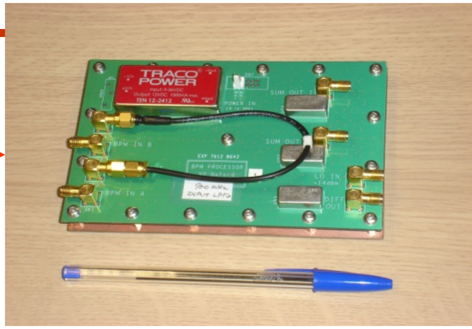
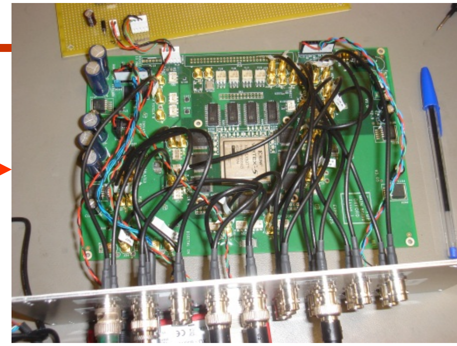
A high-resolution, low-latency beam position monitor (BPM) system has been developed for use in particle accelerators and beam lines that operate with trains of particle bunches with bunch separations as low as several tens of nanoseconds, such as future linear electron-positron colliders and free-electron 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.

Upstream FONT5 System

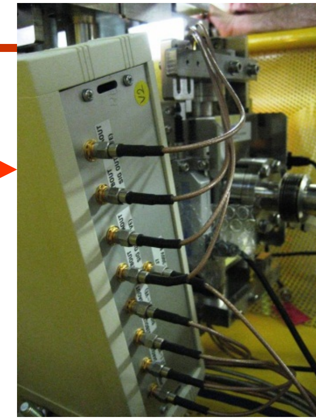


Analogue Front-end

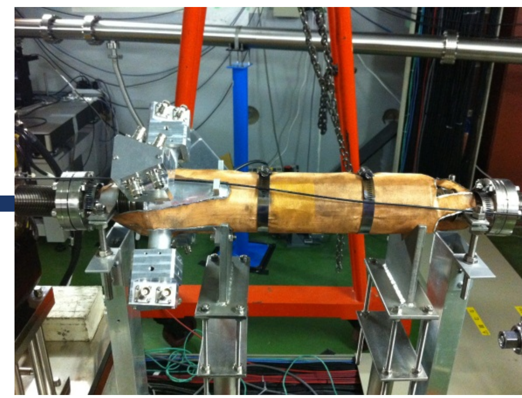
BPM processor



FPGA-based digital processor

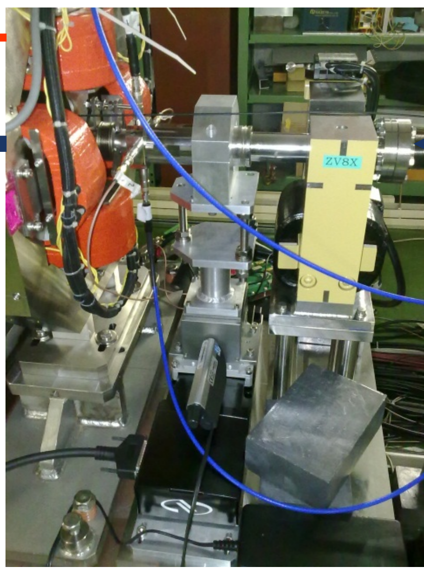


Kicker drive amplifier



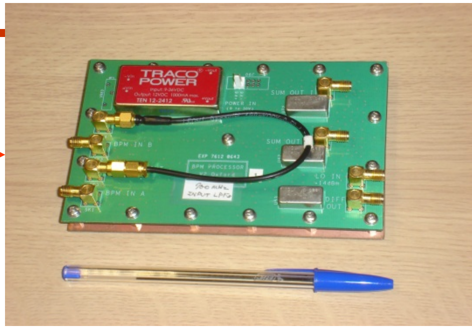
Strip-line kicker

Beam



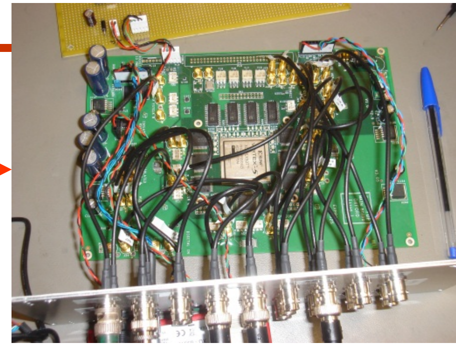
Stripline BPM with mover system

Upstream FONT5 System



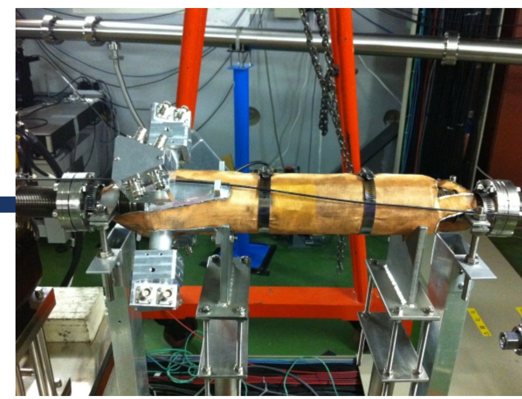
Analogue Front-end

BPM processor



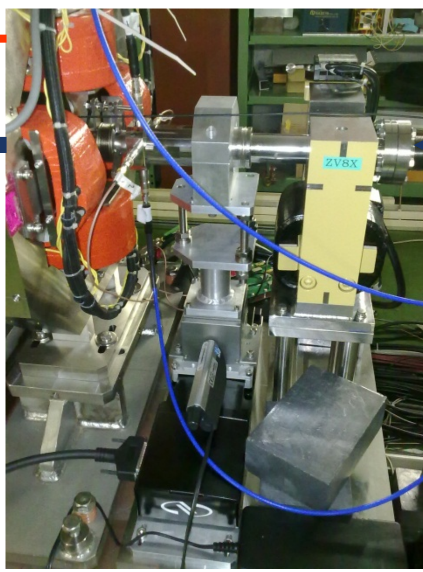
FPGA-based digital processor

Kicker drive amplifier



Strip-line kicker

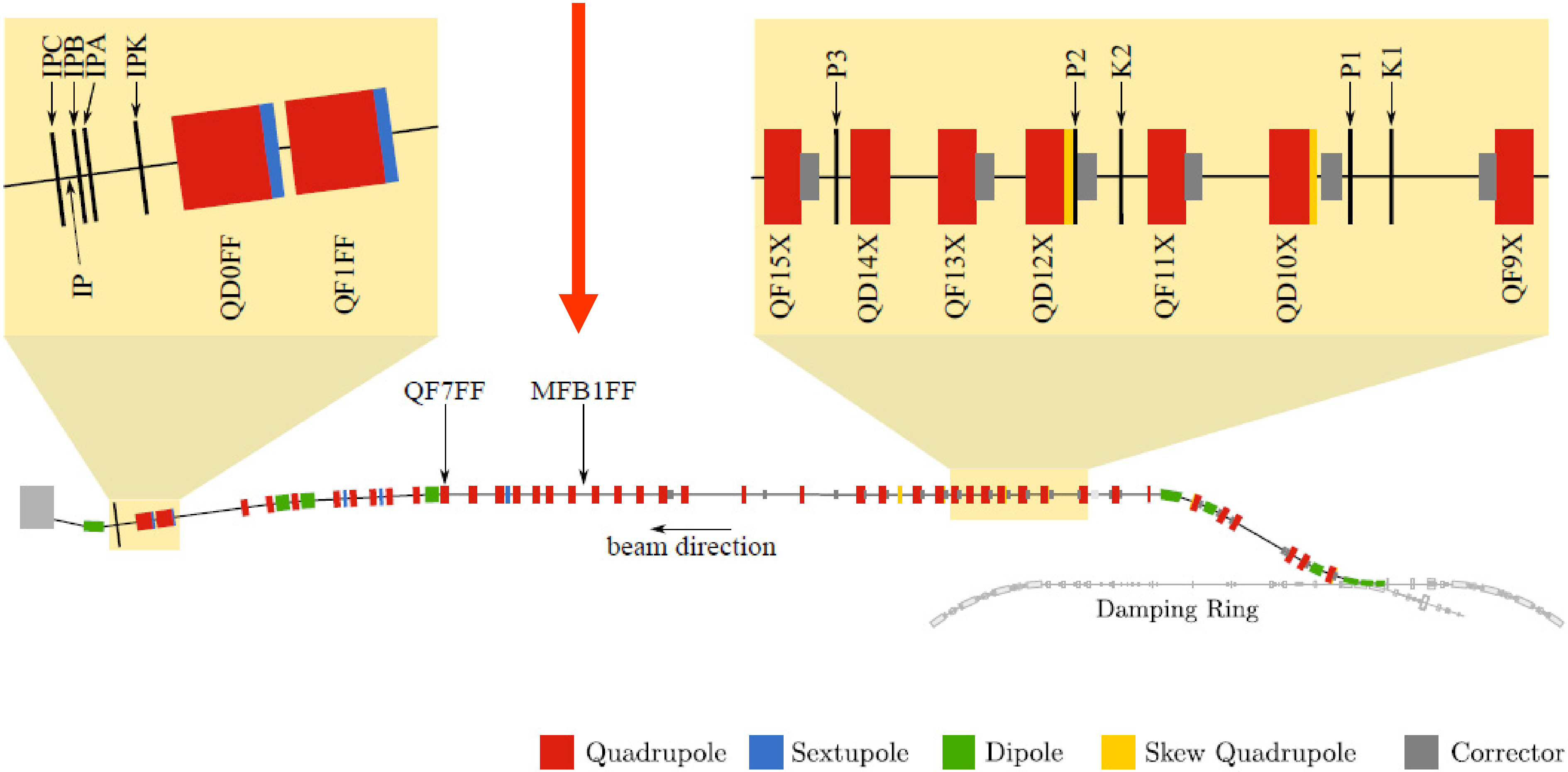
Beam



Stripline BPM with mover system

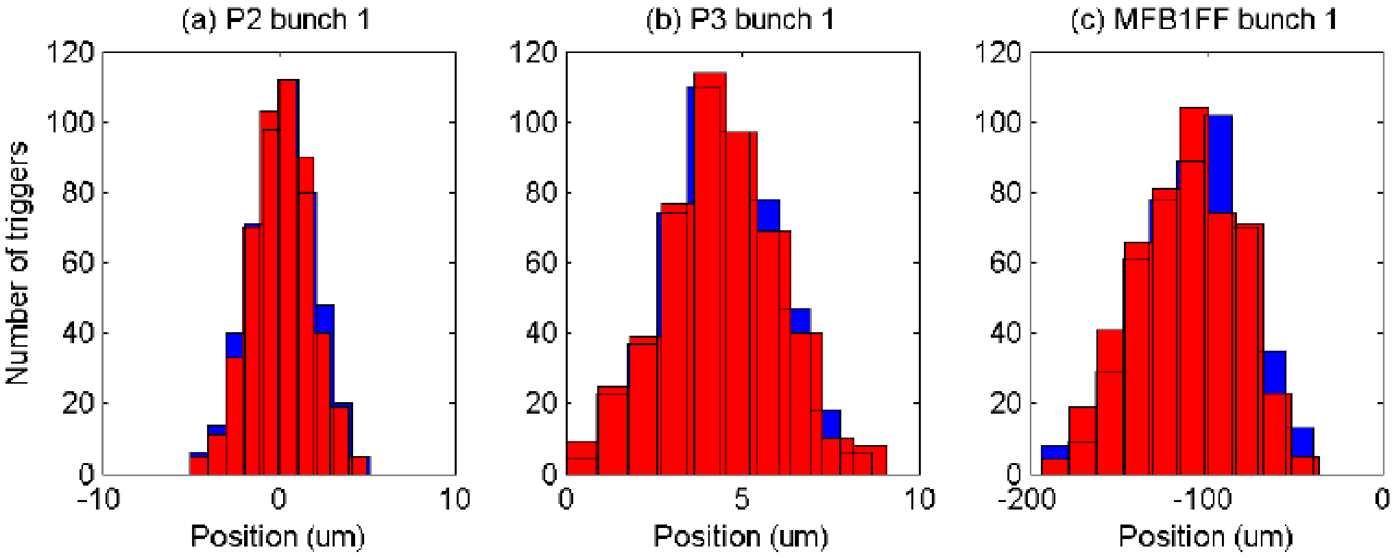
Meets ILC requirements: BPM resolution
Dynamic range
Latency

Witness BPM



IPC
IPB
IPA
IPK
IP
QD0FF
QF1FF
P3
P2
K2
P1
K1
QF15X
QD14X
QF13X
QD12X
QF11X
QD10X
QF9X
QF7FF
MFB1FF
beam direction
Damping Ring
Quadrupole
Sextupole
Dipole
Skew Quadrupole
Corrector

FONT5 system performance

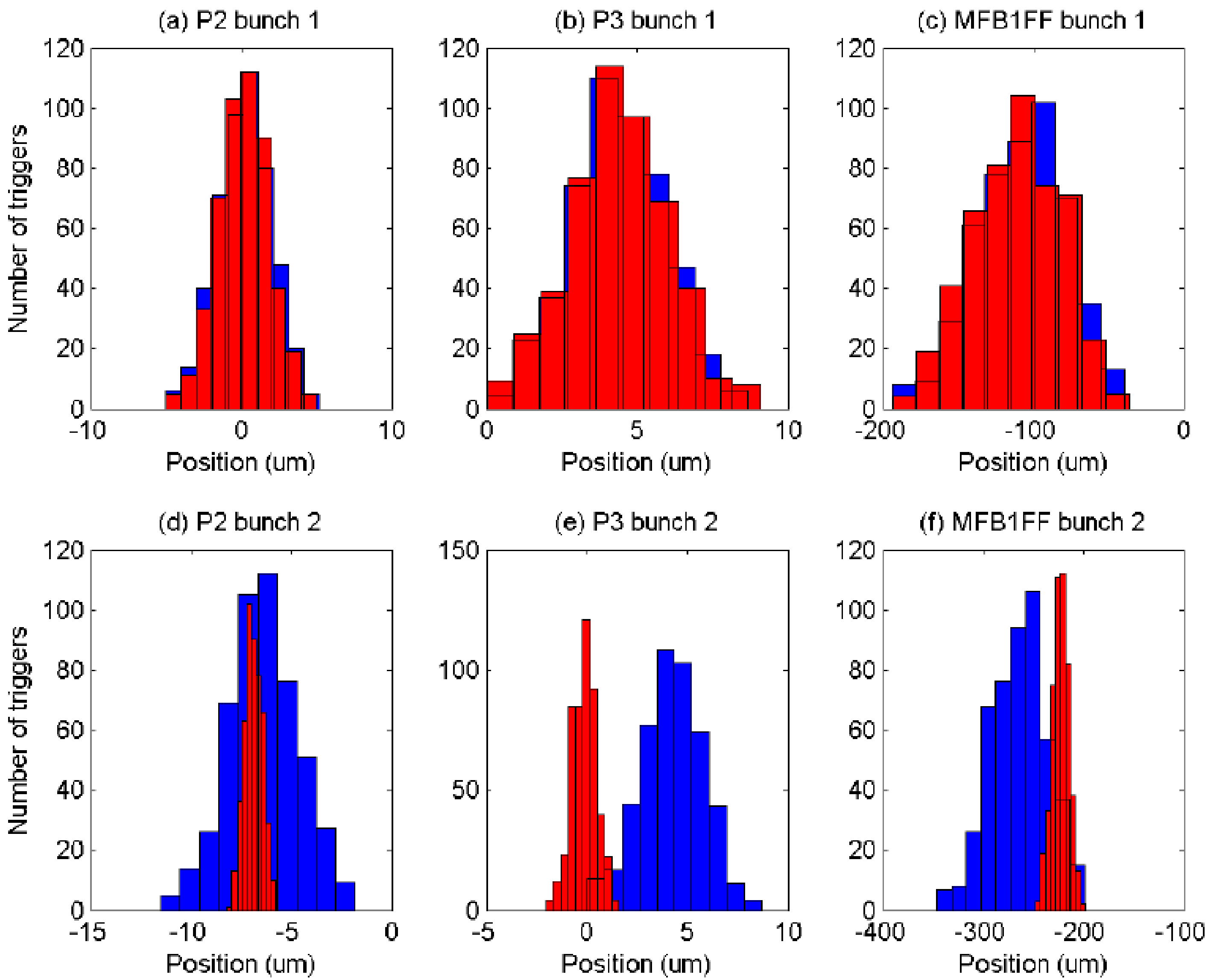


Bunch 1: input to FB

FB off

FB on

FONT5 system performance



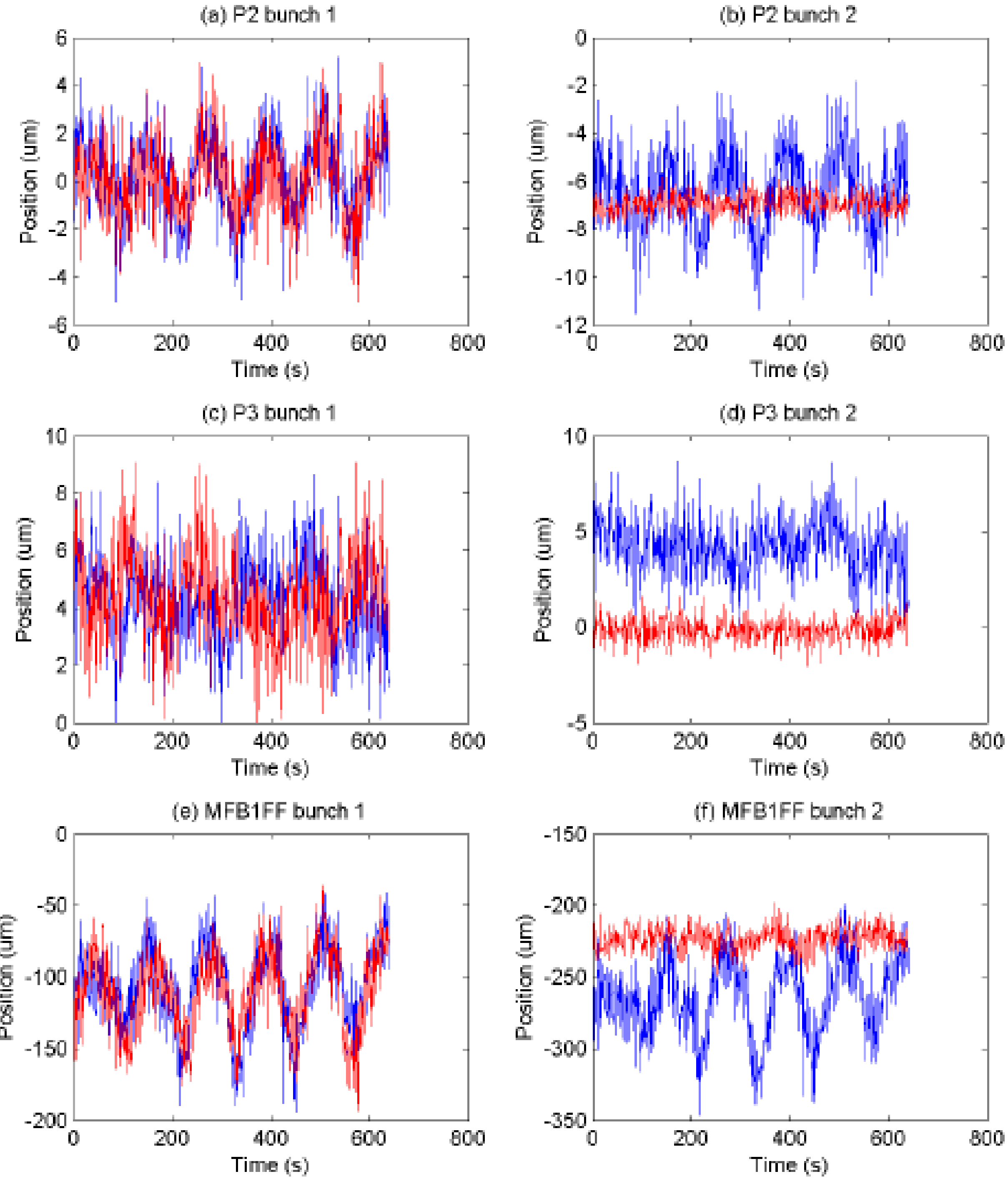
Bunch 1: input to FB

FB off
FB on

Bunch 2: corrected

FB off
FB on

Time sequence



Bunch 2: corrected

FB off

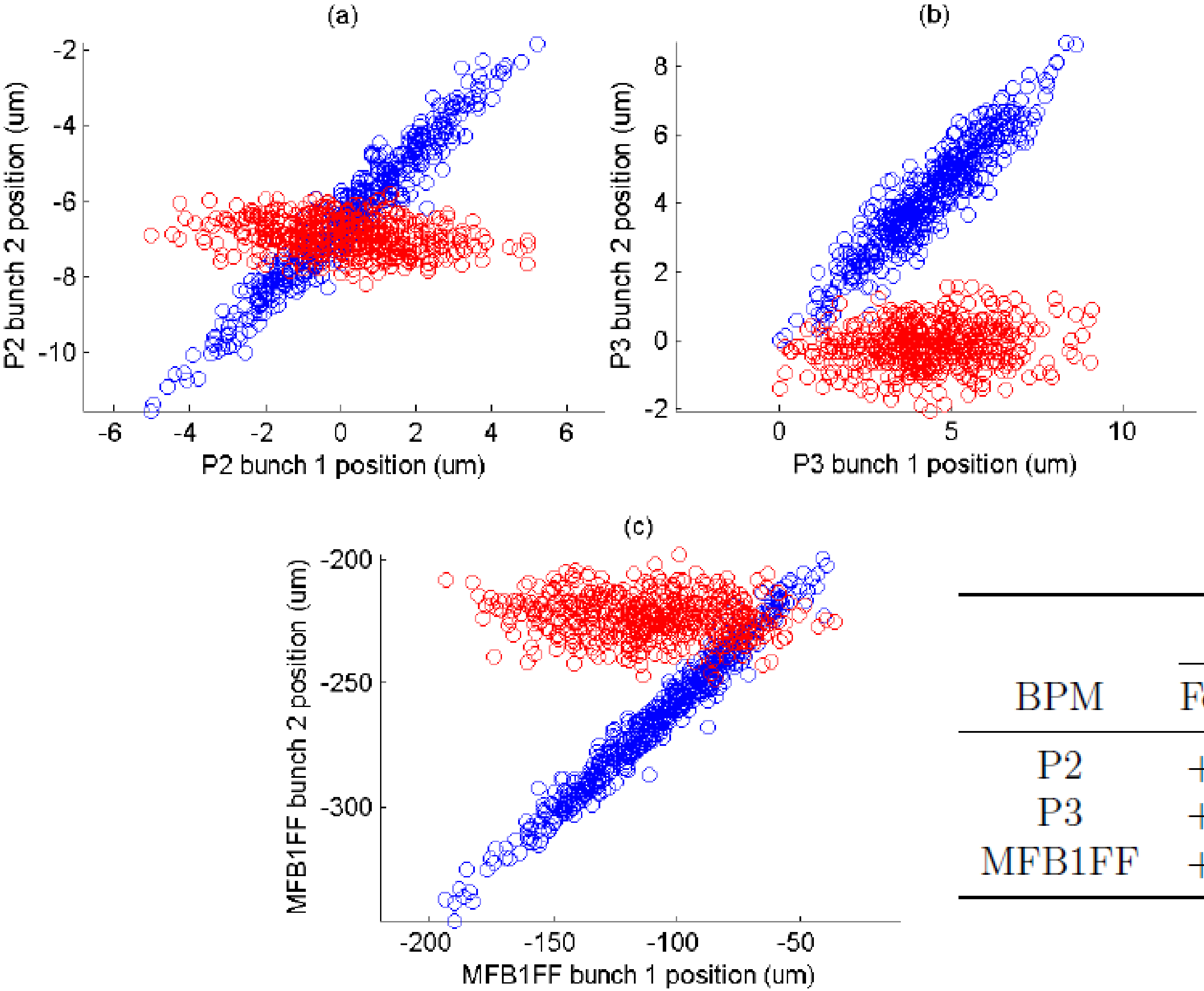
FB on

Jitter reduction

	Position jitter (μm)			
	Bunch 1		Bunch 2	
BPM	Feedback off	Feedback on	Feedback off	Feedback on
P2	1.80 ± 0.06	1.70 ± 0.05	1.74 ± 0.06	0.44 ± 0.01
P3	1.56 ± 0.05	1.66 ± 0.05	1.55 ± 0.05	0.61 ± 0.02
MFB1FF	29.9 ± 1.0	29.4 ± 0.9	27.5 ± 0.9	8.3 ± 0.3

Factor ~ 3.5 improvement

Bunch 1 – bunch 2 correlation

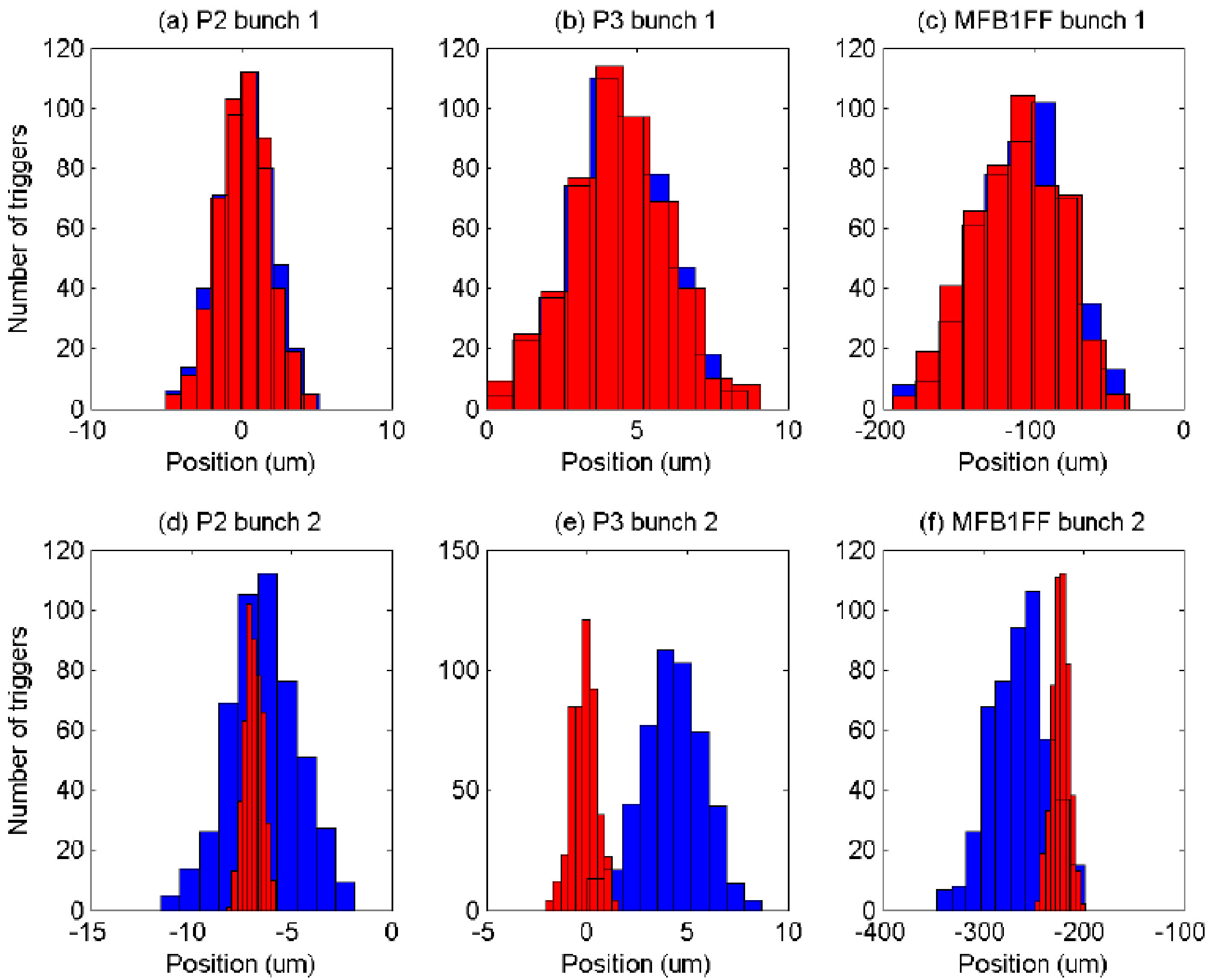


FB off

FB on

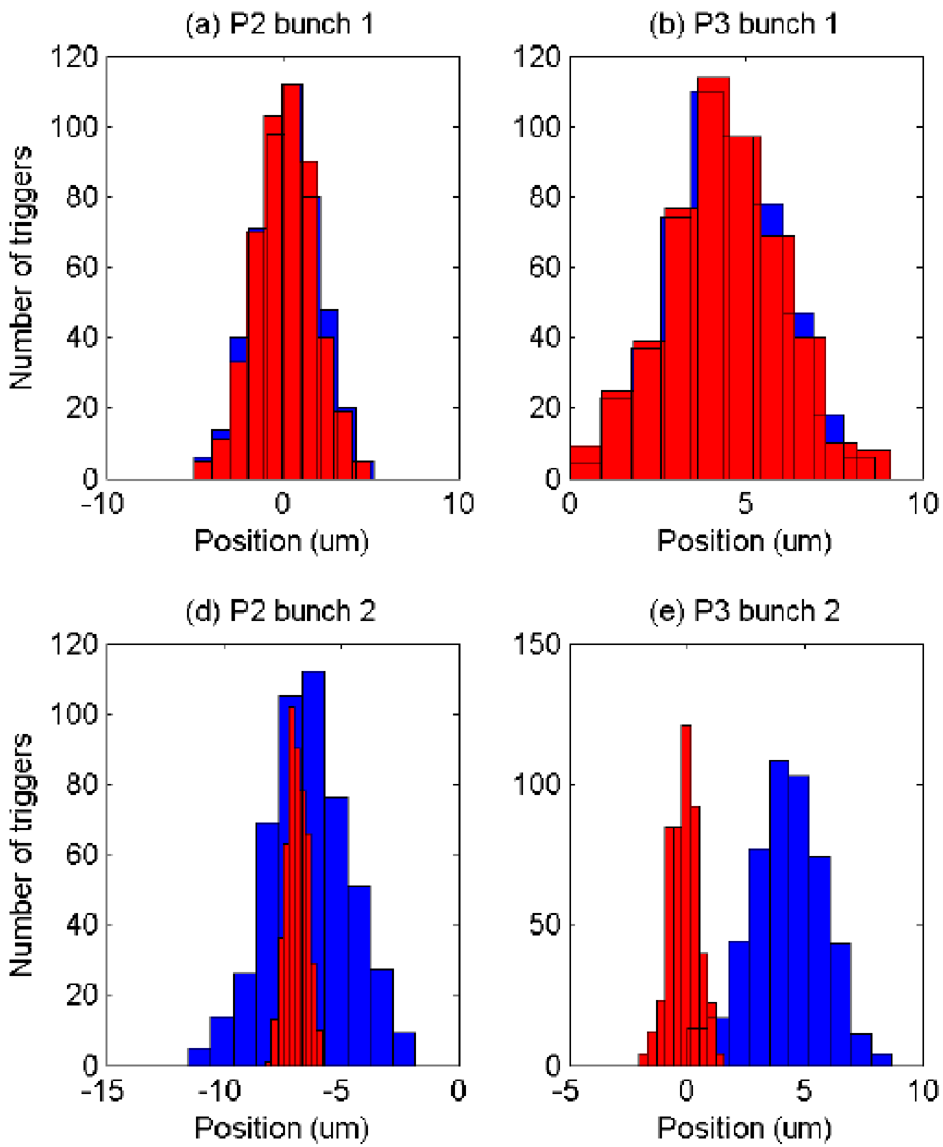
	ρ_{12} (%)	
BPM	Feedback off	Feedback on
P2	$+96.9 \pm 0.3$	-25 ± 4
P3	$+93.3 \pm 0.6$	$+15 \pm 4$
MFB1FF	$+98.3 \pm 0.2$	-14 ± 4

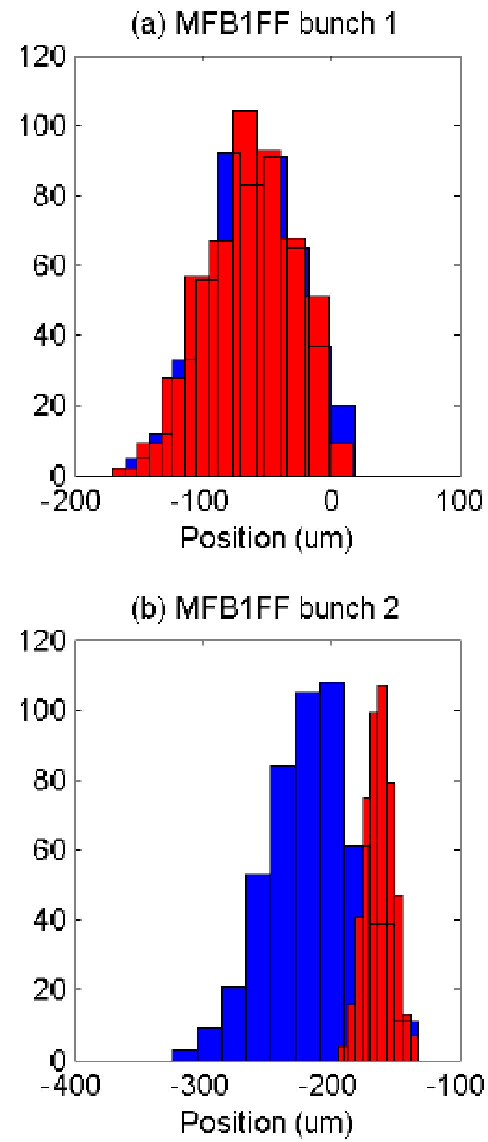
Feedback loop witness



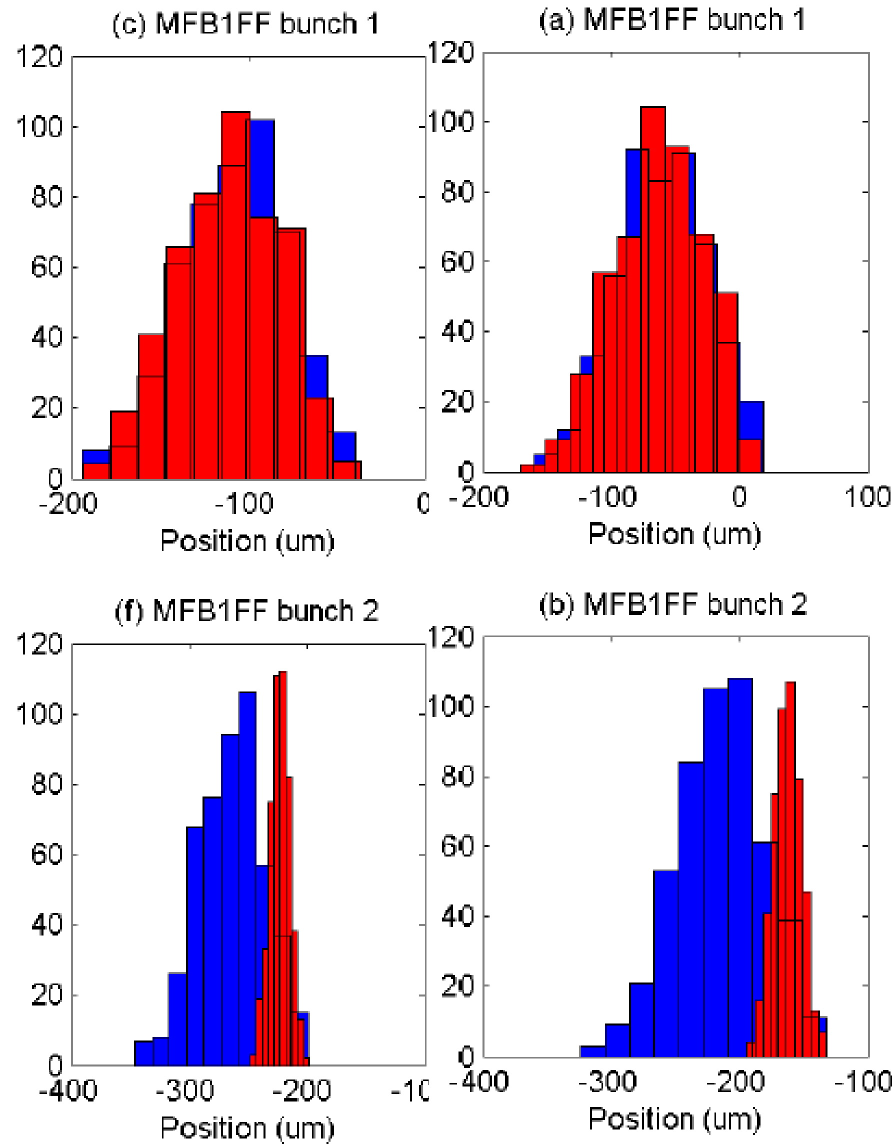
Feedback loop

predict

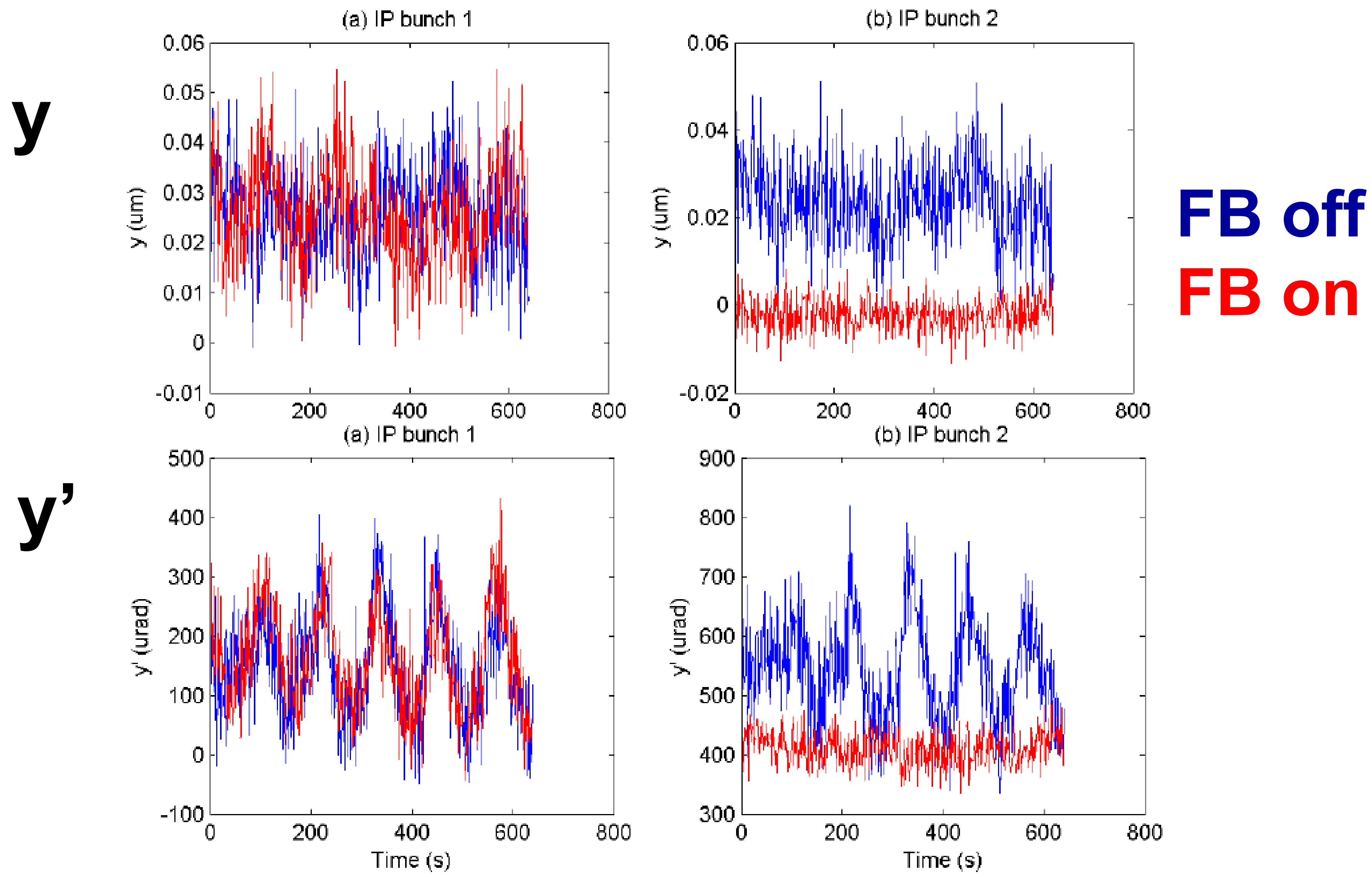




Witness BPM: measure predict



Predicted jitter reduction at IP



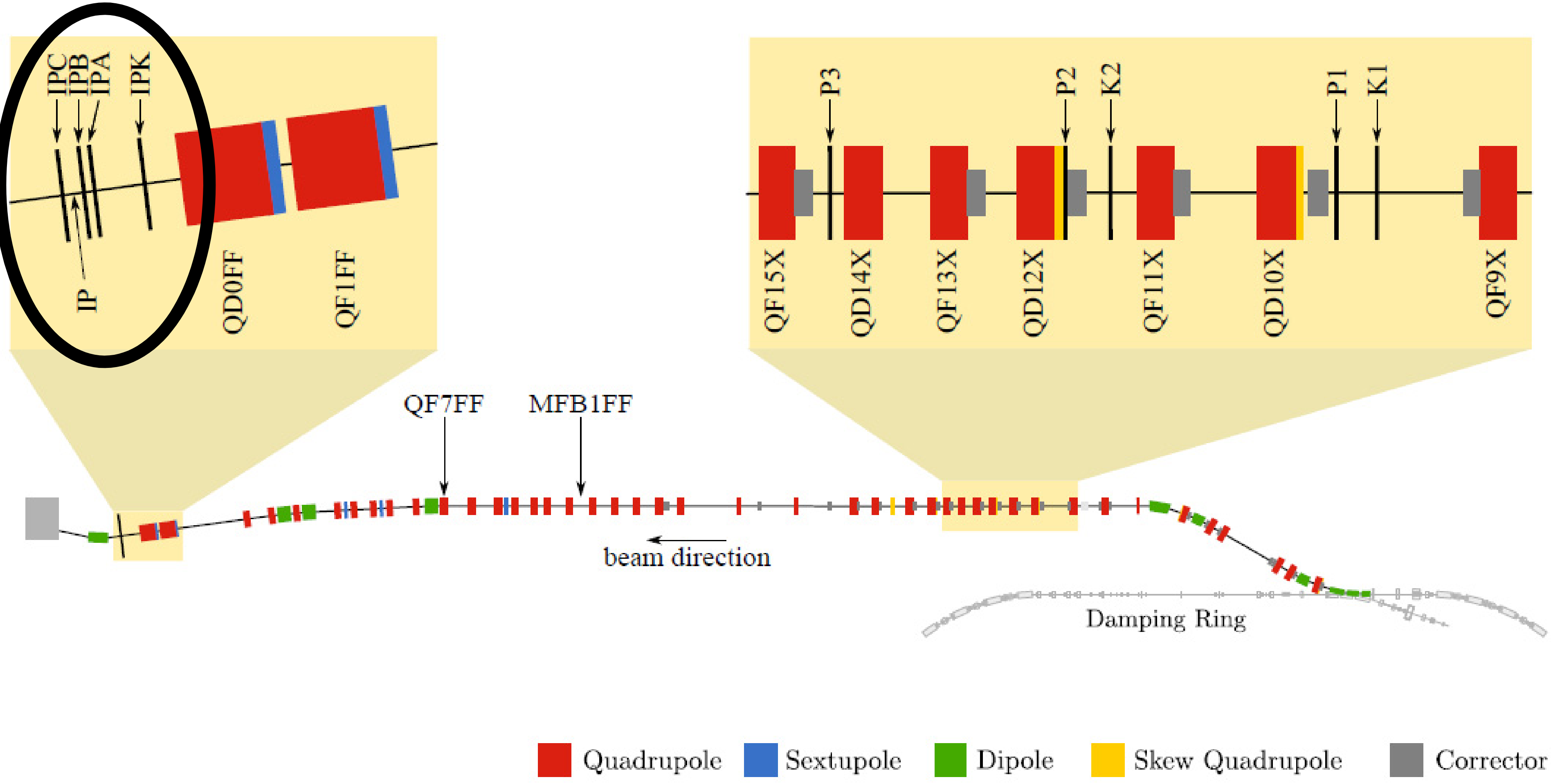
Predicted jitter reduction at IP

	Position y jitter (nm)		Angle y' jitter (urad)	
Bunch	Feedback off	Feedback on	Feedback off	Feedback on
1	9.5 ± 0.3	10.1 ± 0.3	89 ± 3	87 ± 3
2	9.4 ± 0.3	3.6 ± 0.1	87 ± 3	28 ± 1

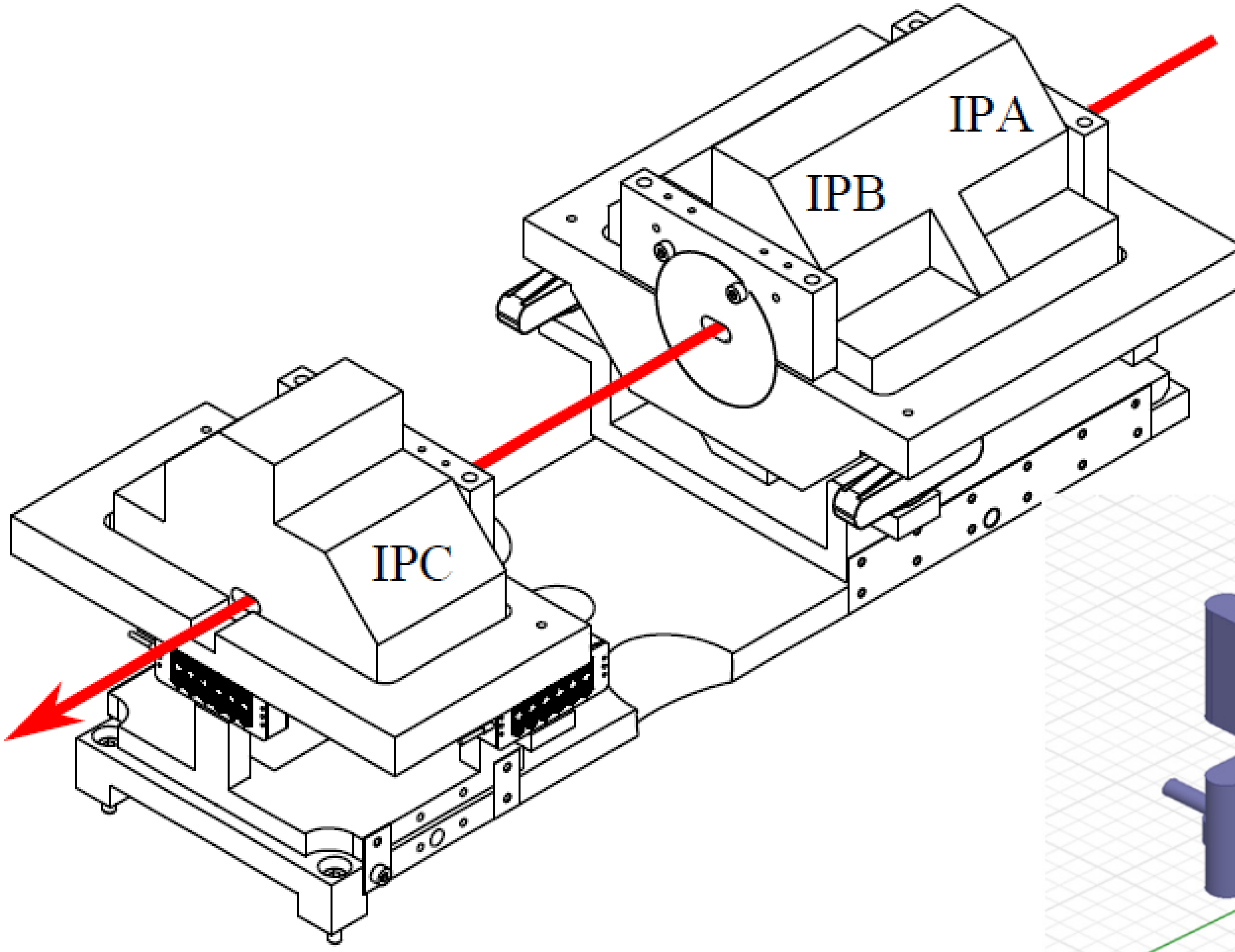
Predict position stabilised at few nanometre level…

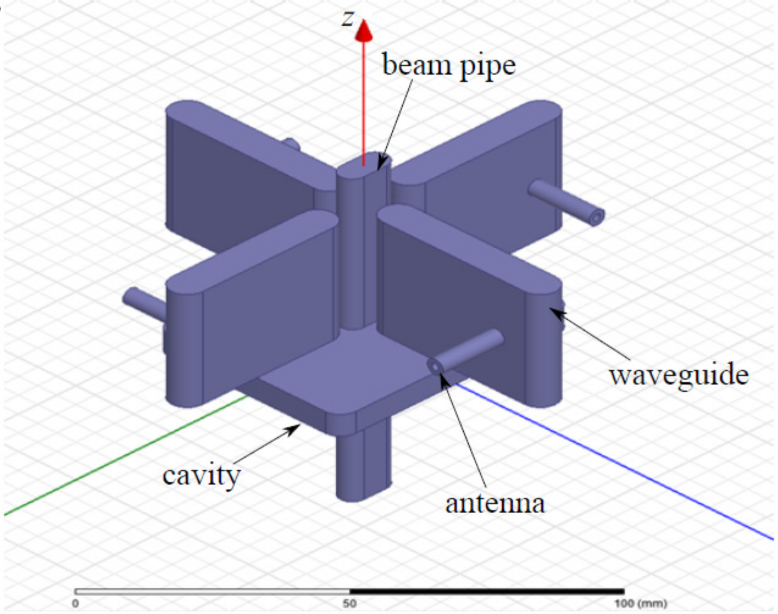
How to measure it?!

Cavity BPM system near IP



IP cavity BPM system



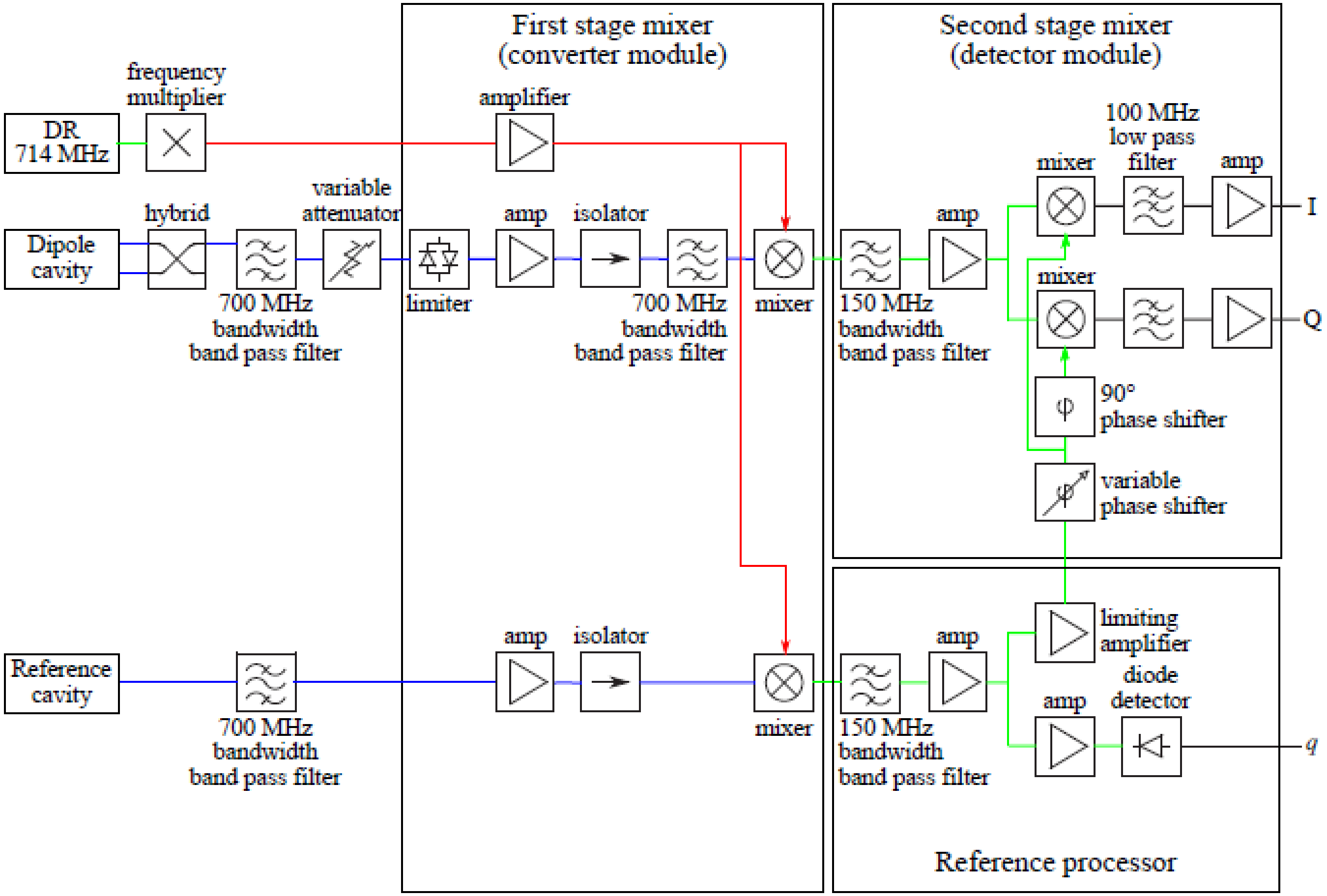


Low-Q cavity BPMs

Design parameters

Parameter			Dipole cavities x port	Dipole cavities y port	Reference cavities x cavity	Reference cavities y cavity
Resonant frequency	f_{mn}	(GHz)	5.712	6.426	5.711	6.415
Internal quality factor	$(Q_0)_{mn}$		4959	4670	1201	1229
Decay time	τ_{mn}	(ns)	18.72	17.23	33.16	30.03

Cavity BPM signal processing



I → I'

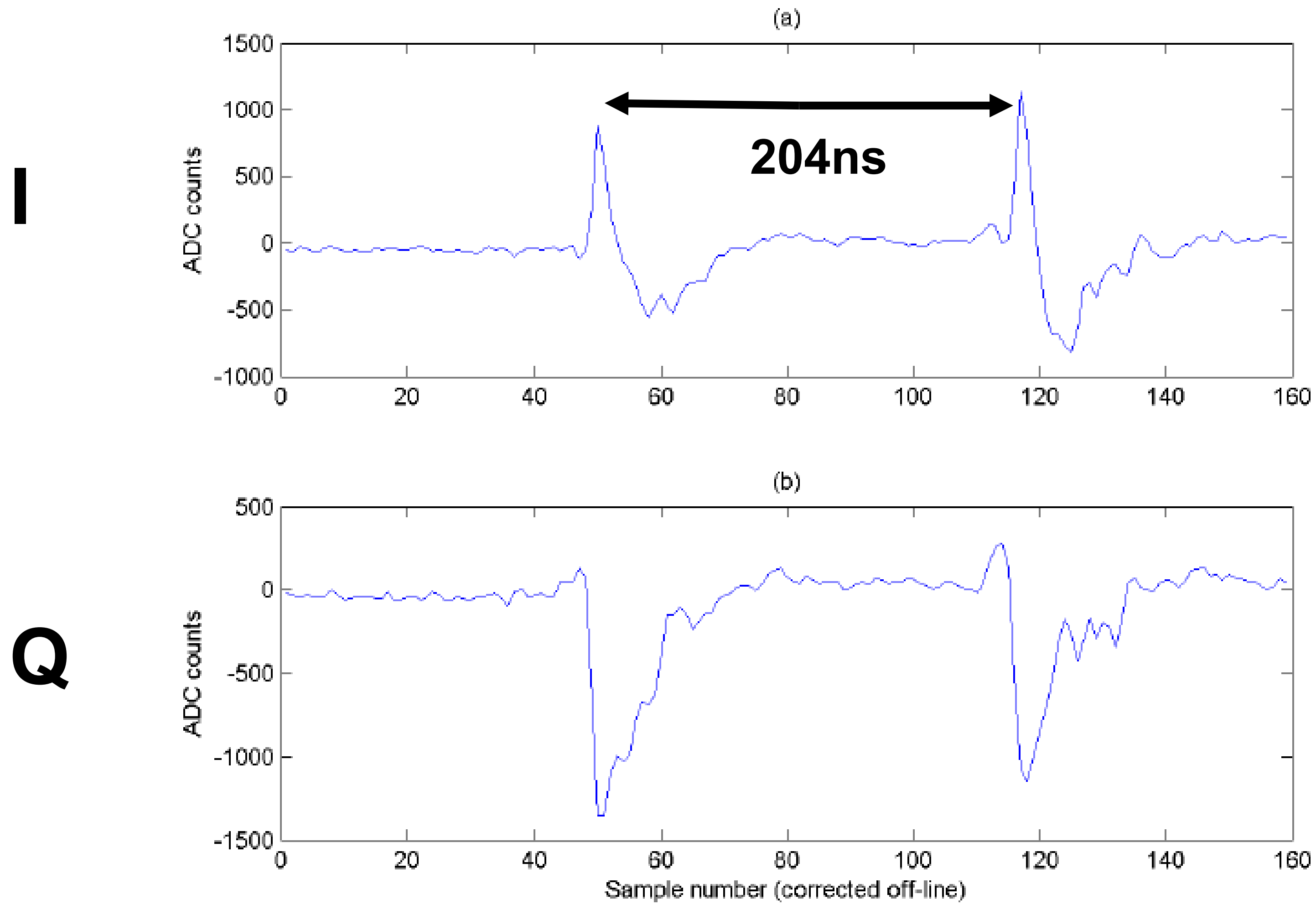
Q → Q'

bunch charge

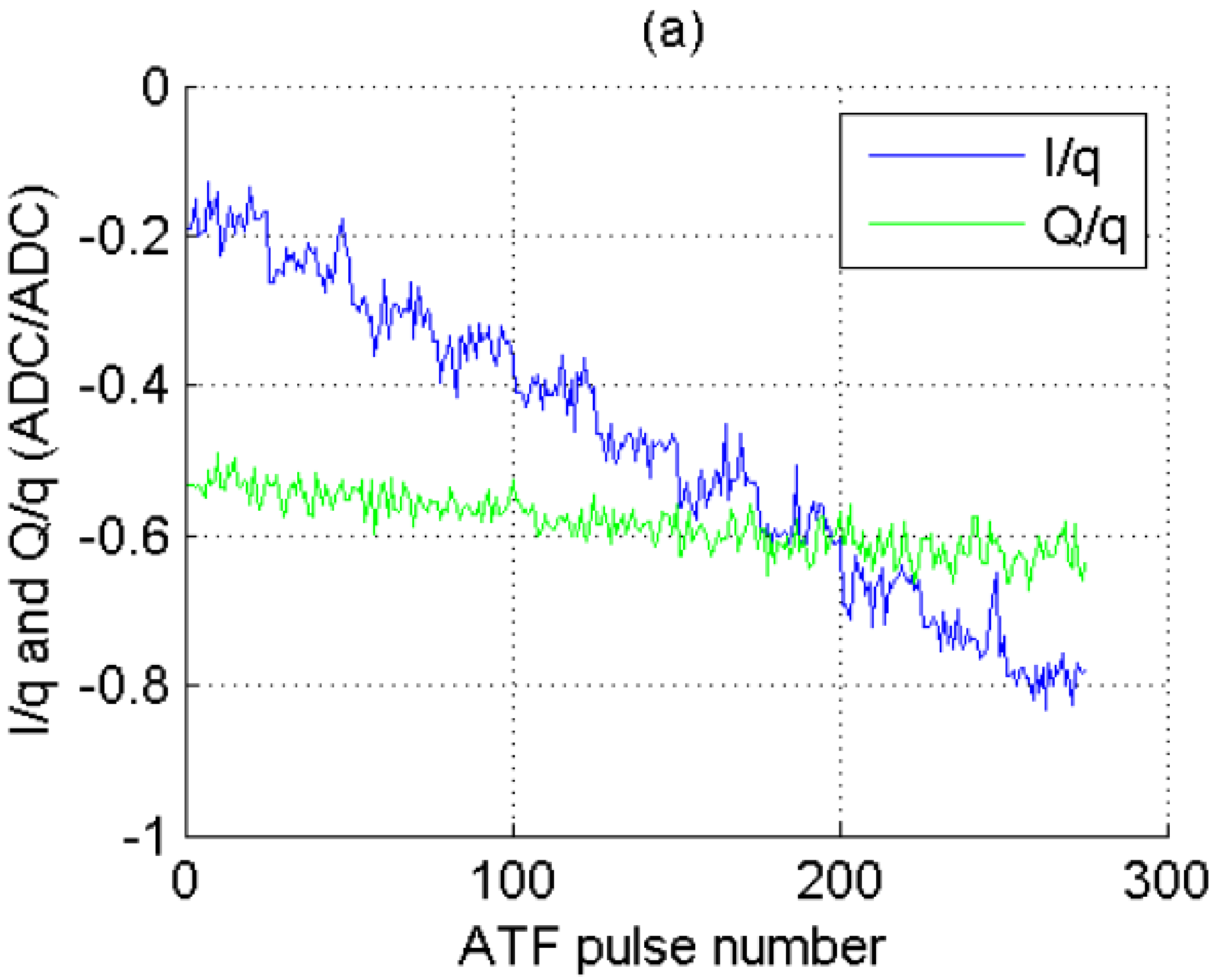
Honda

Cavity BPM outputs (2-bunch train)

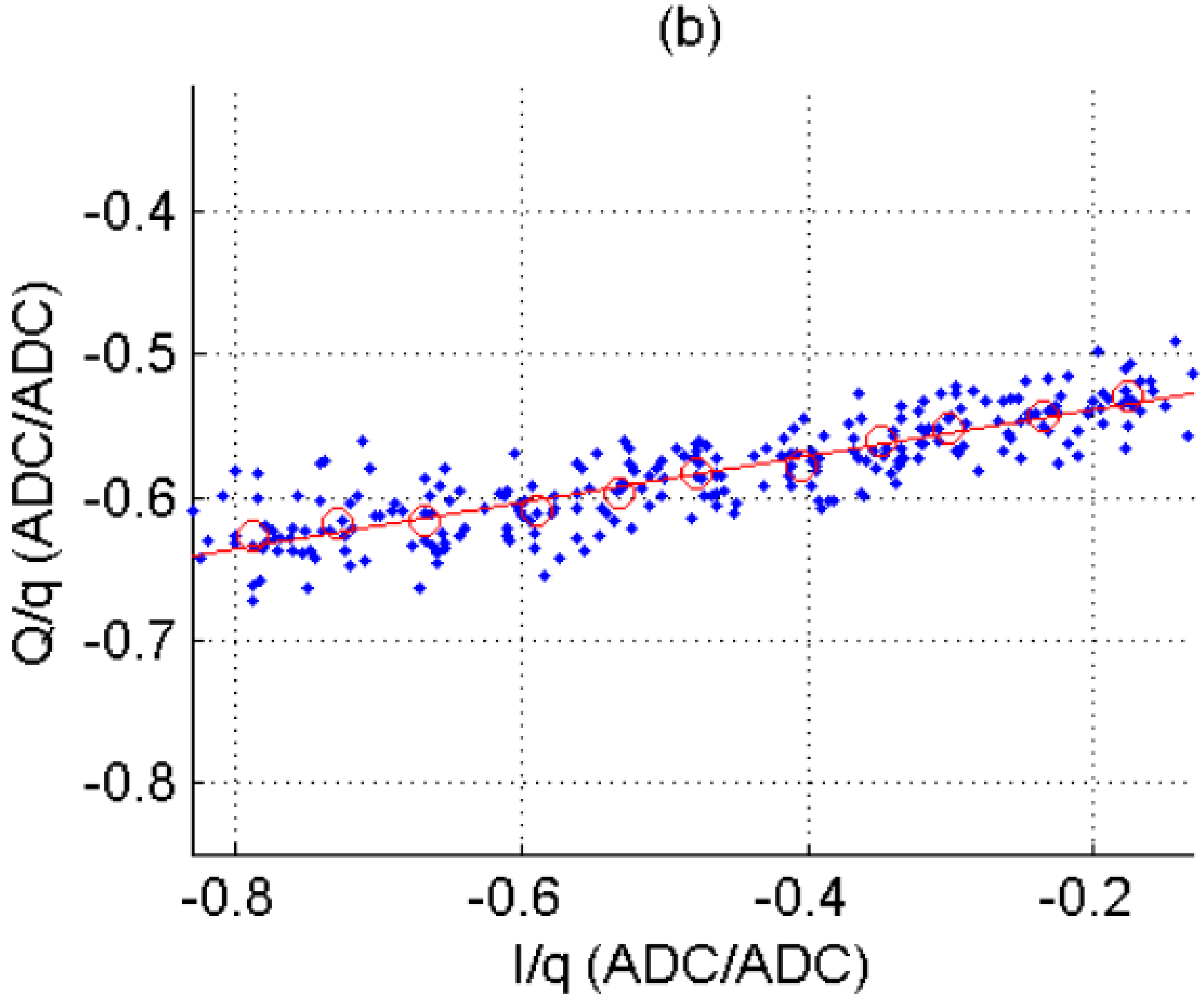
Single-shot measurement



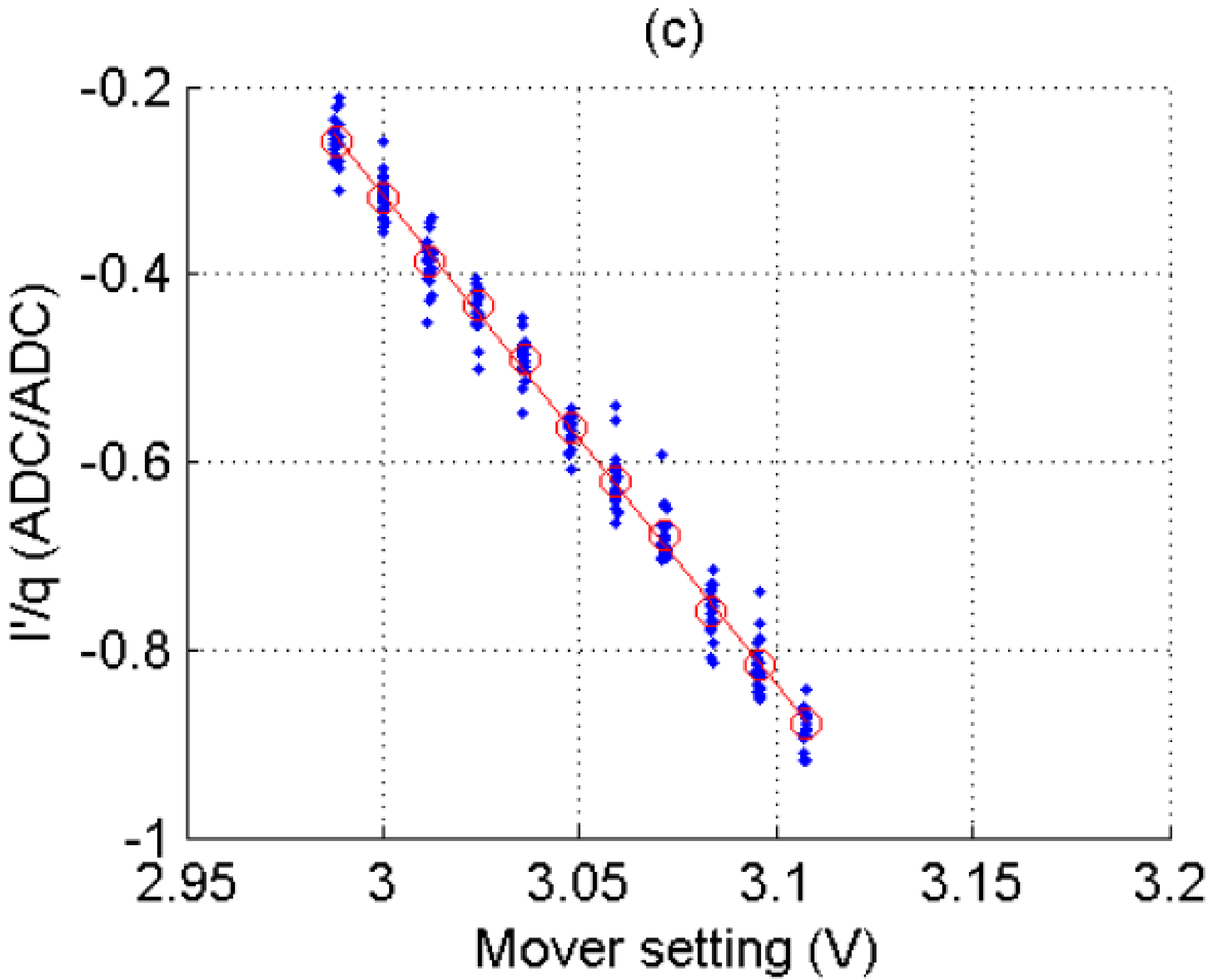
Example position calibration: 1)



Example position calibration: 2)



Example position calibration: 3)



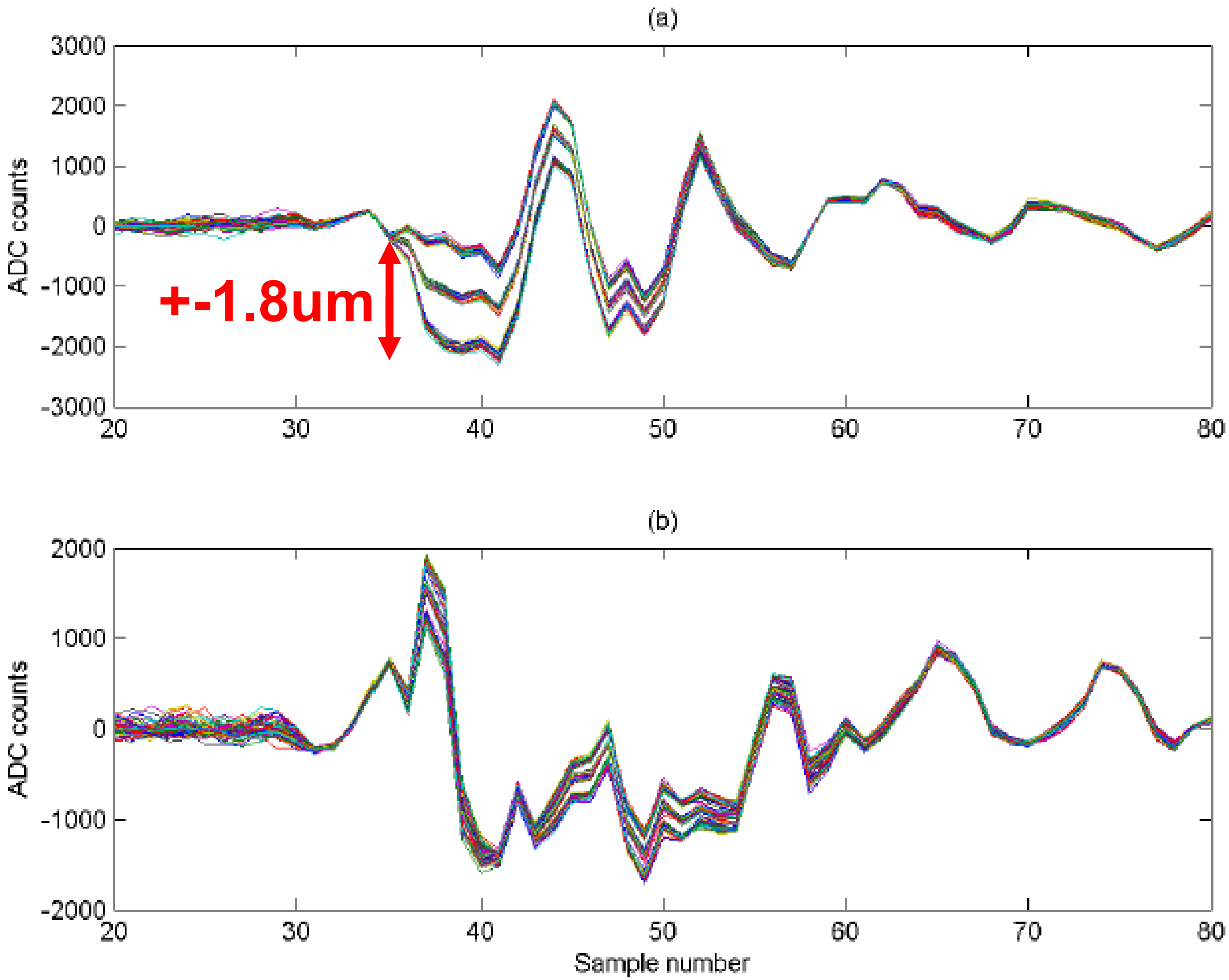
Comments

- **Signal levels → saturation → non-linear response**
- **Dynamic range ←→ resolution**
- **Operate with (remotely controlled) attenuation**
- **Optimal resolution (0db) →**
  dynamic range +- 3um w.r.t. nominal centre
- **Beam setup + beam quality are critical**

Waveforms at 0db – ugly!

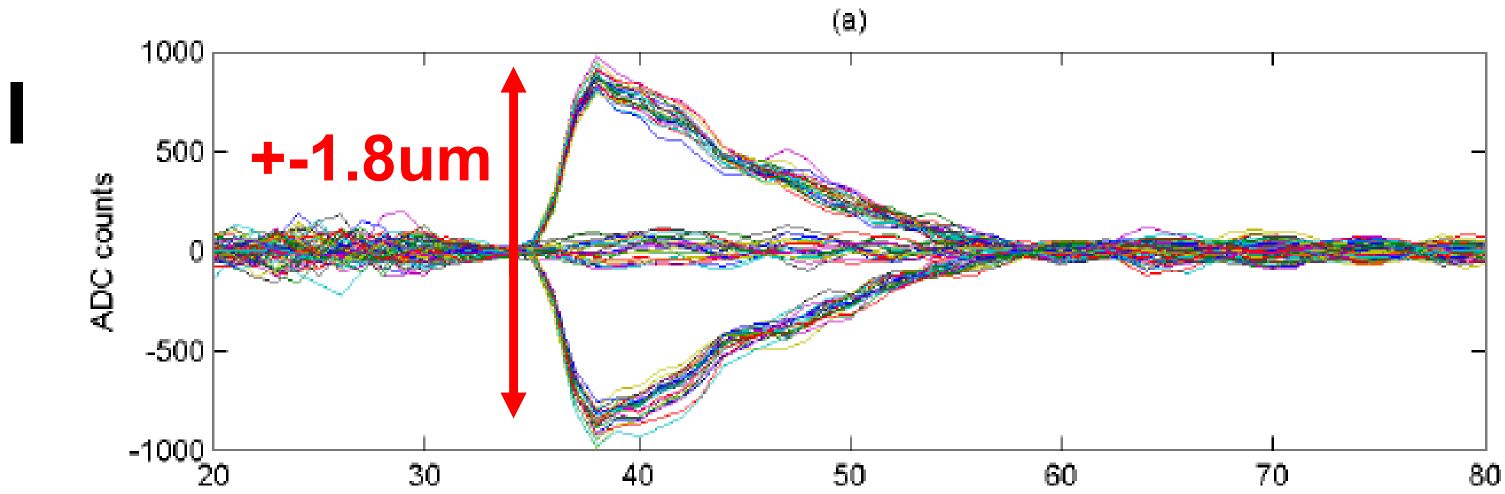
I

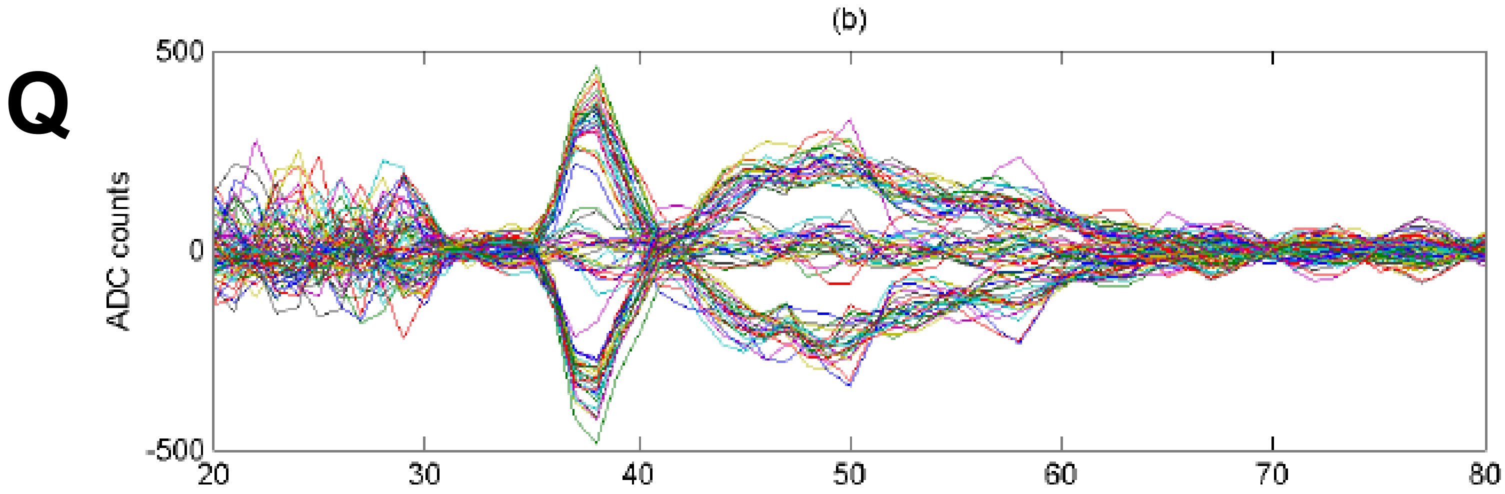
Q



Position information superposed on static artefact

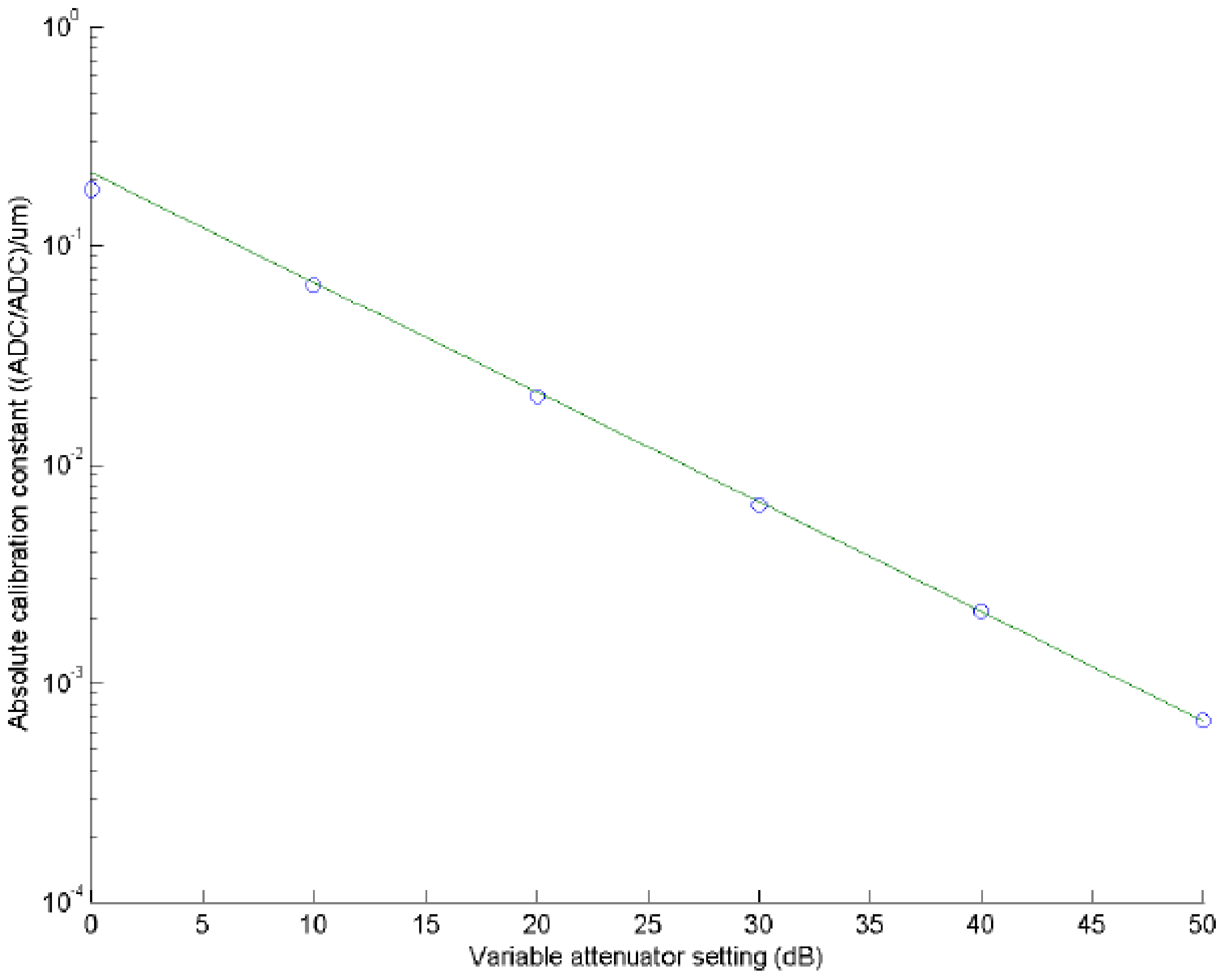
Mean-subtracted waveforms



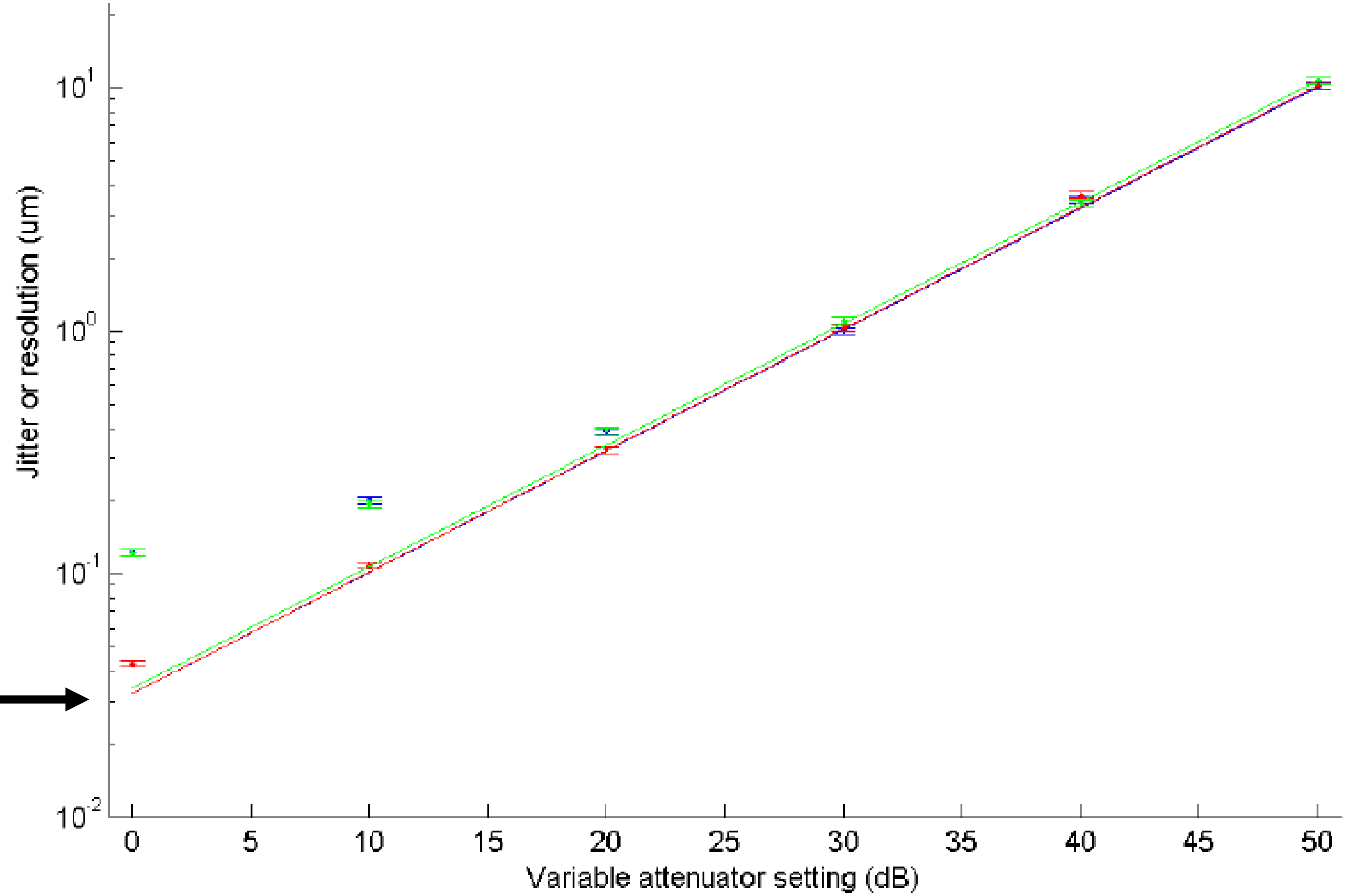


BPM response vs. attenuation

position calibration scale



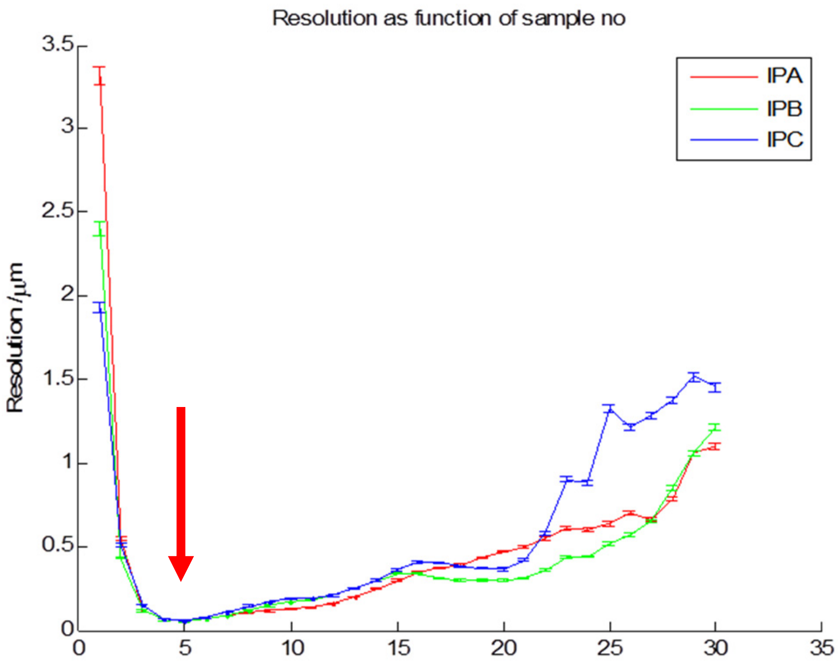
Beam jitter vs. attenuation



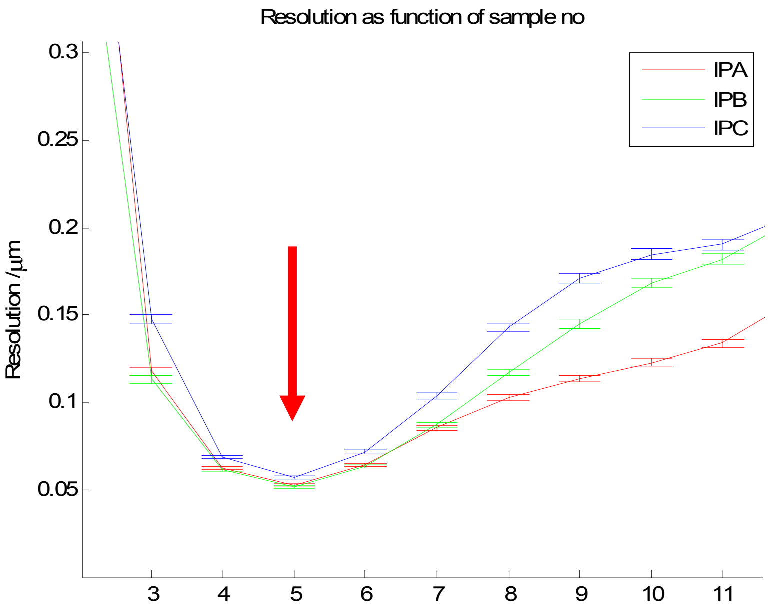
Noise floor ~ 30nm

Resolution vs. sample # (0db)

Fitting method

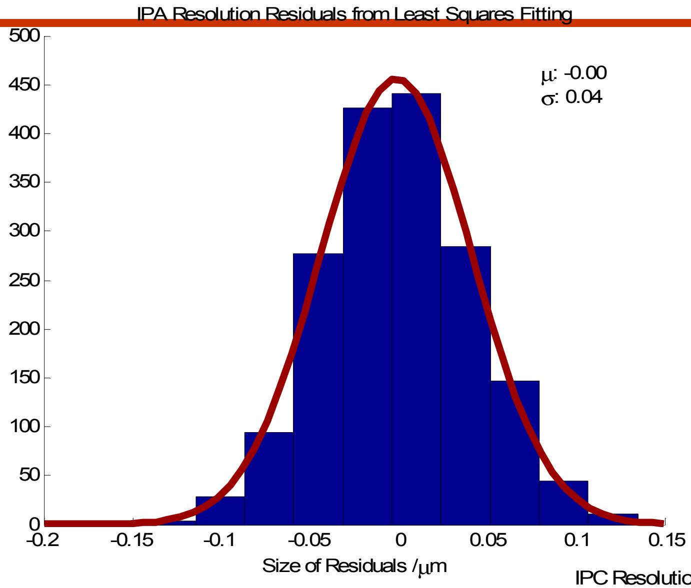


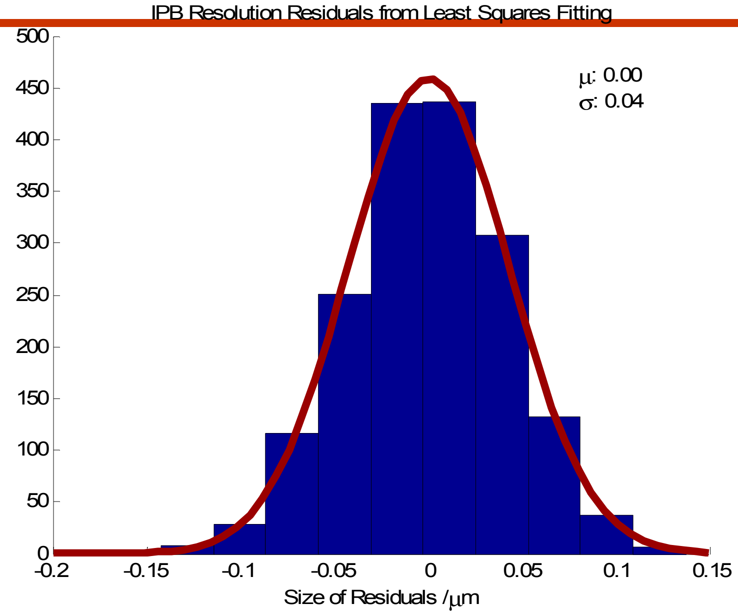
Geometric method

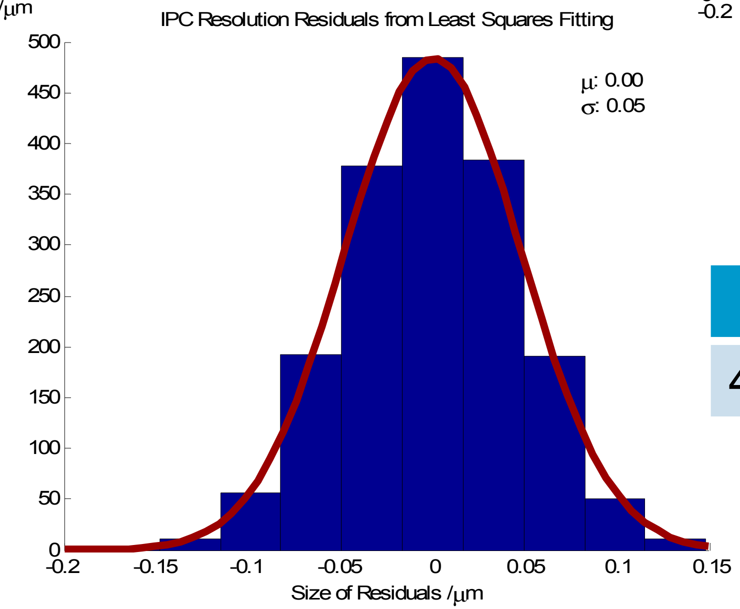


Fitting			Geom
52nm	52nm	57nm	54nm

Resolution – integrate samples 3 - 10

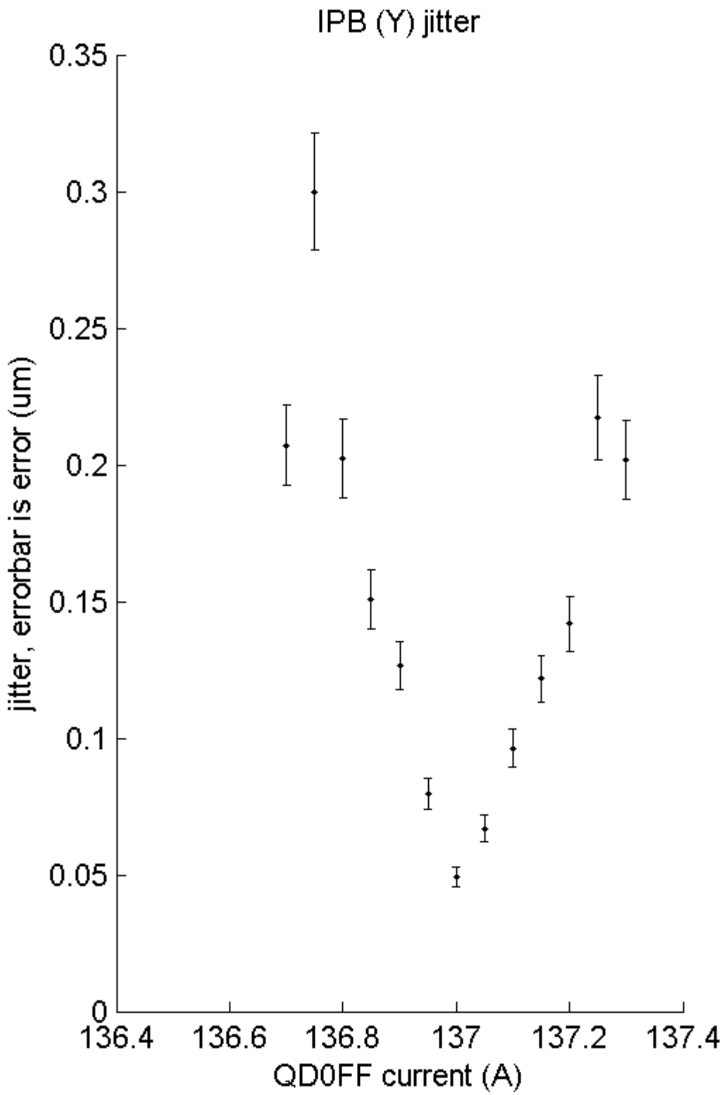






Fitting			Geom
42nm	42nm	47nm	55nm

Jitter vs. QD0FF setting (waist scan)



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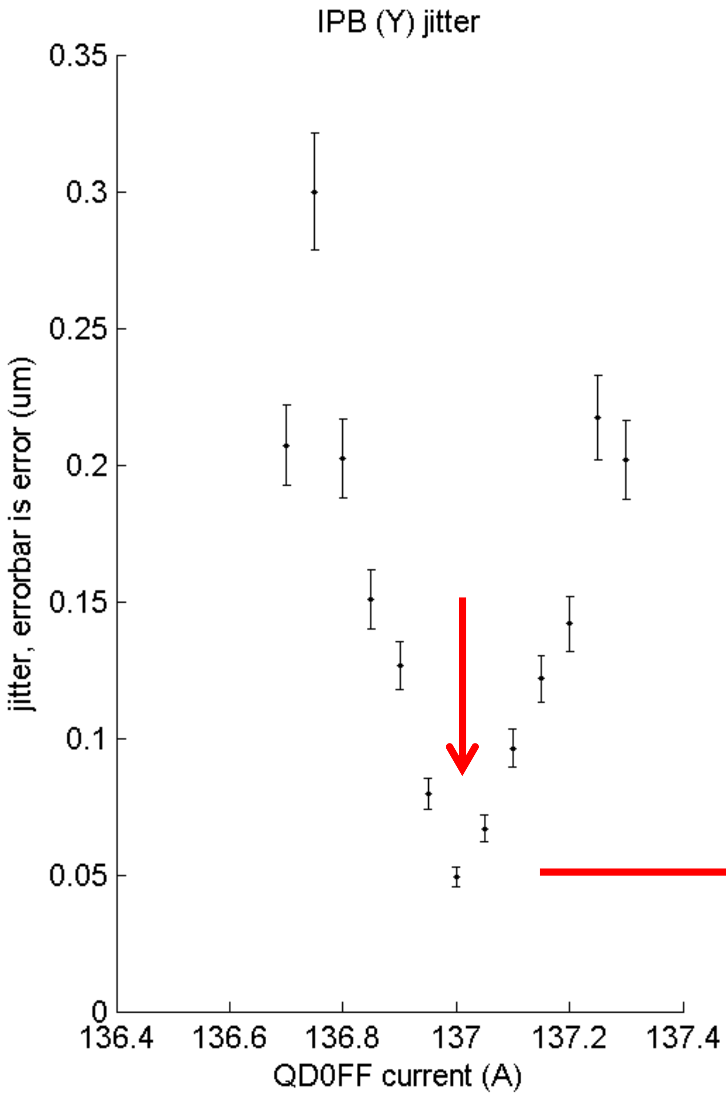
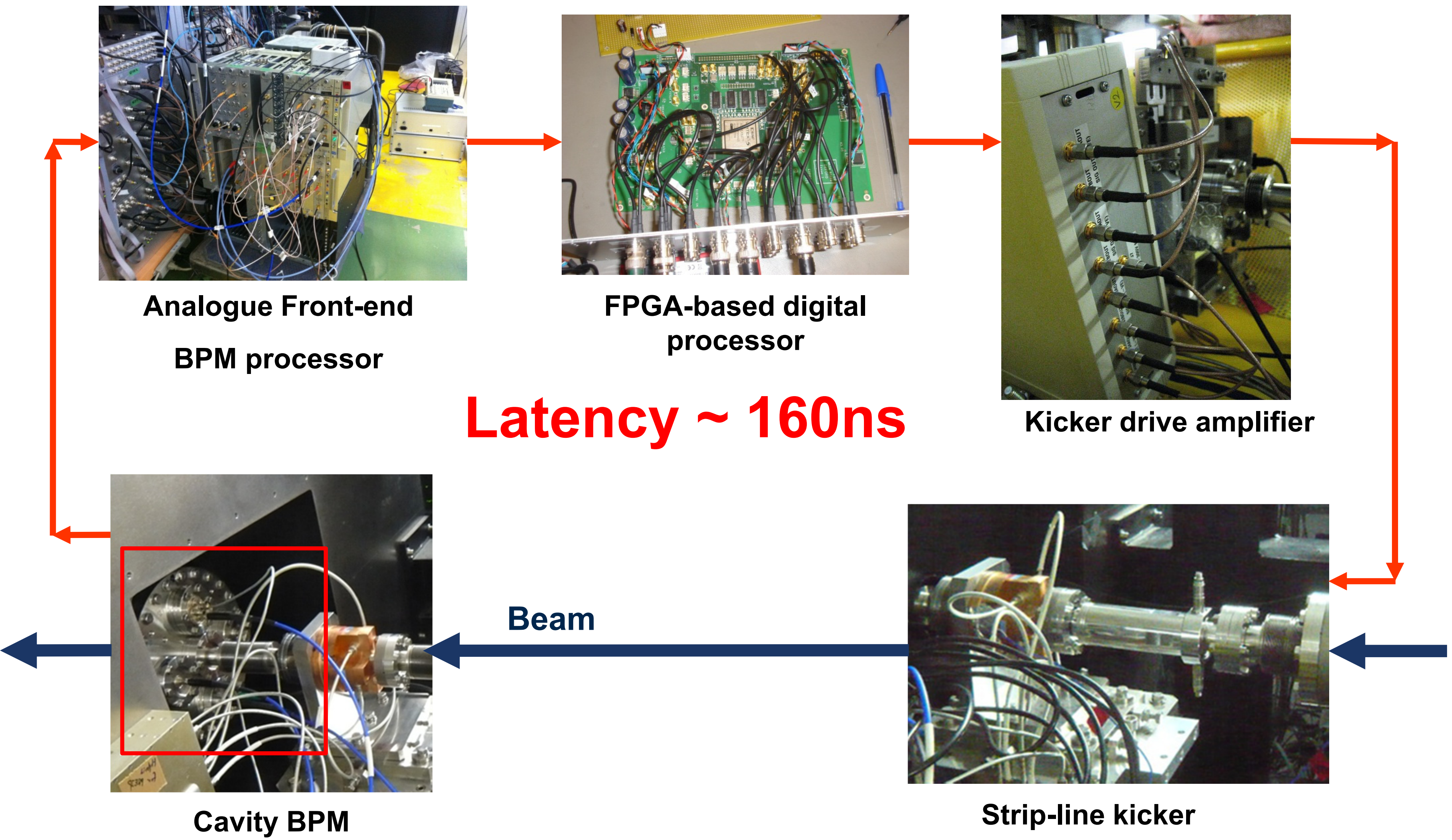


minimum jitter:

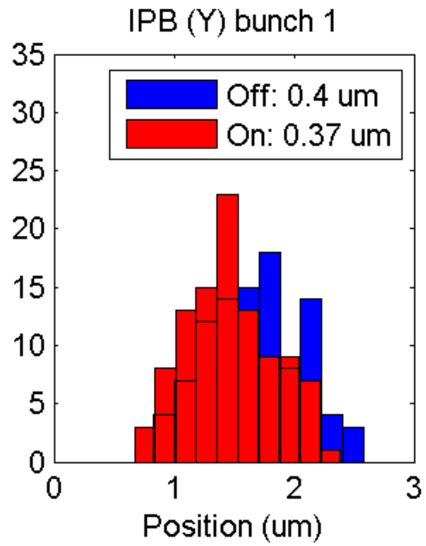
49 nm (integration)

Interaction Point FONT System

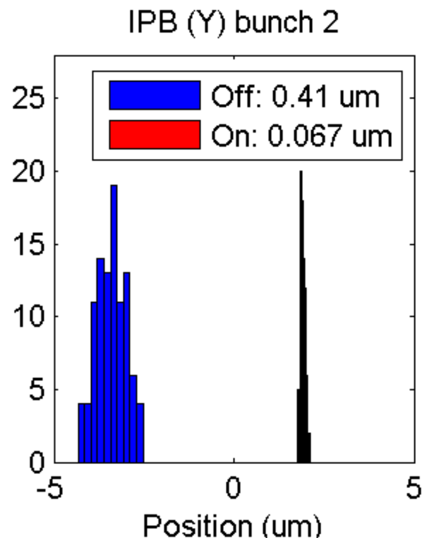


IPFB results

Bunch 1:
not corrected,
jitter ~ 400nm



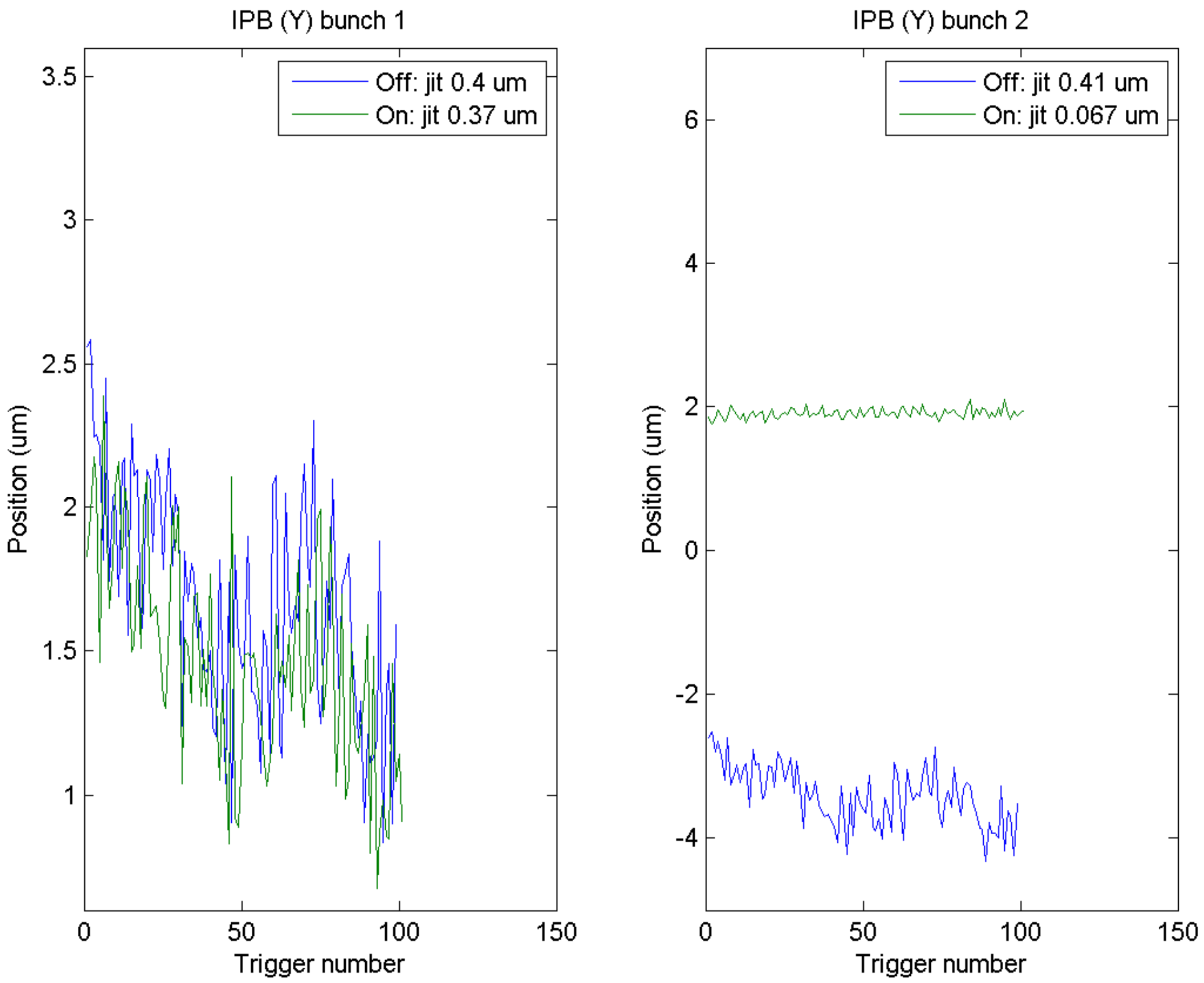
Bunch 2:
corrected,
jitter ~ 67nm



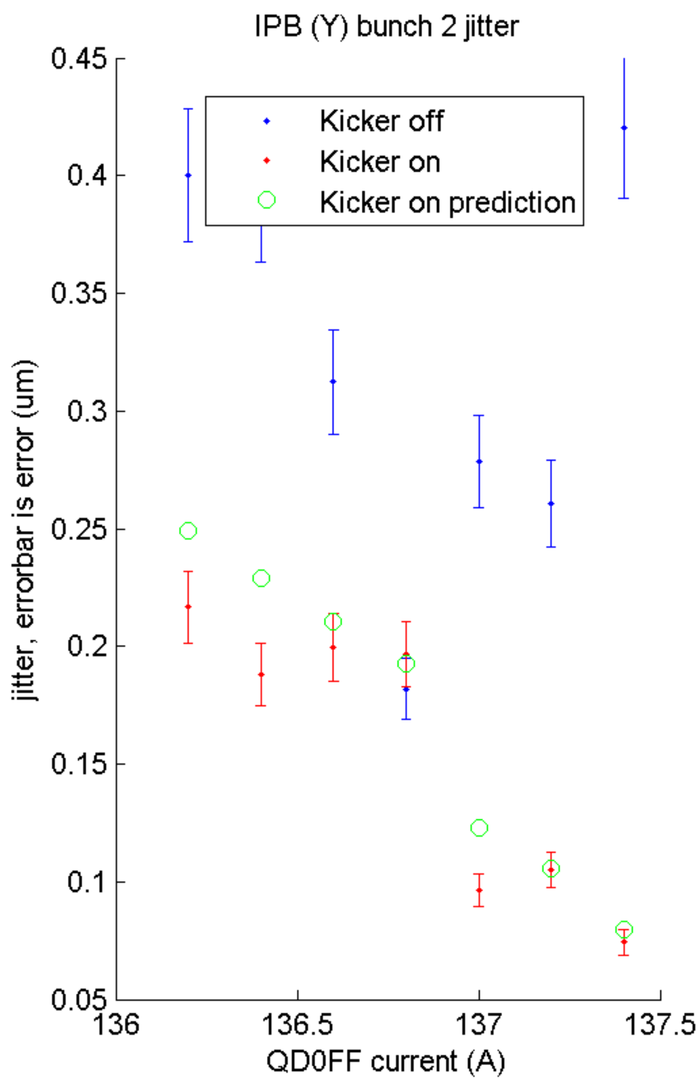
Corrected jitter 67nm

→ resolution 47nm

IPFB results: time sequence



IPFB performance vs. QD0FF setting



Prediction based on incoming jitters of bunches 1 and 2 and measured bunch 1-2 correlation, assuming perfect FB

Summary

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

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Work ongoing to understand/improve cavity BPM resolution

Postscript

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