Progress towards electron-beam feedback at the nanometre level,

for linear colliders and FELs, at the KEK/ATF2

Feedback On Nanosecond Timescales (FONT)

Philip Burrows

Neven Blaskovic, Talitha Bromwich, Glenn Christian, Colin Perry,

Rebecca Ramjiawan

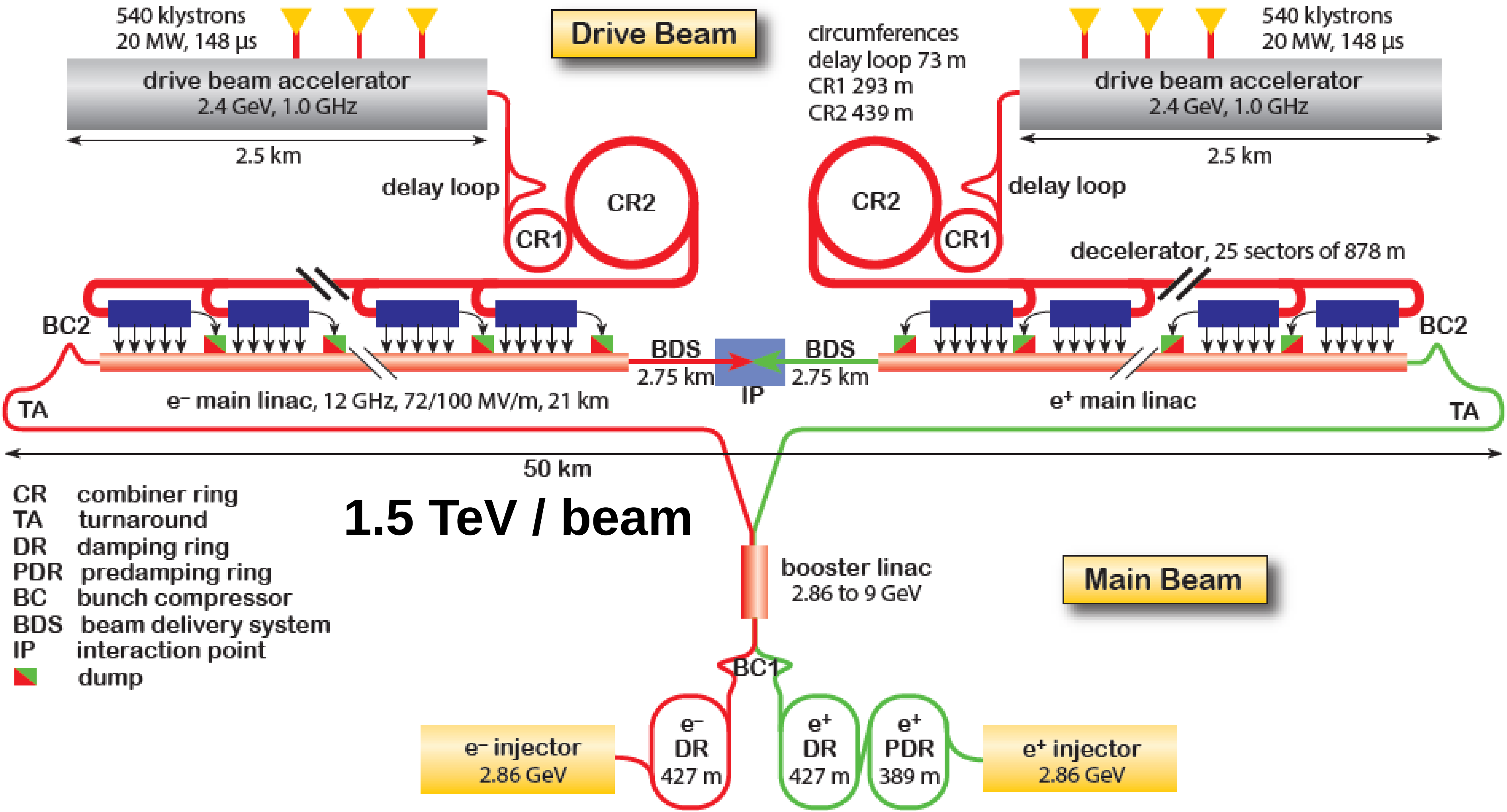
John Adams Institute, Oxford University

in collaboration with: KEK, KNU, LAL

Outline

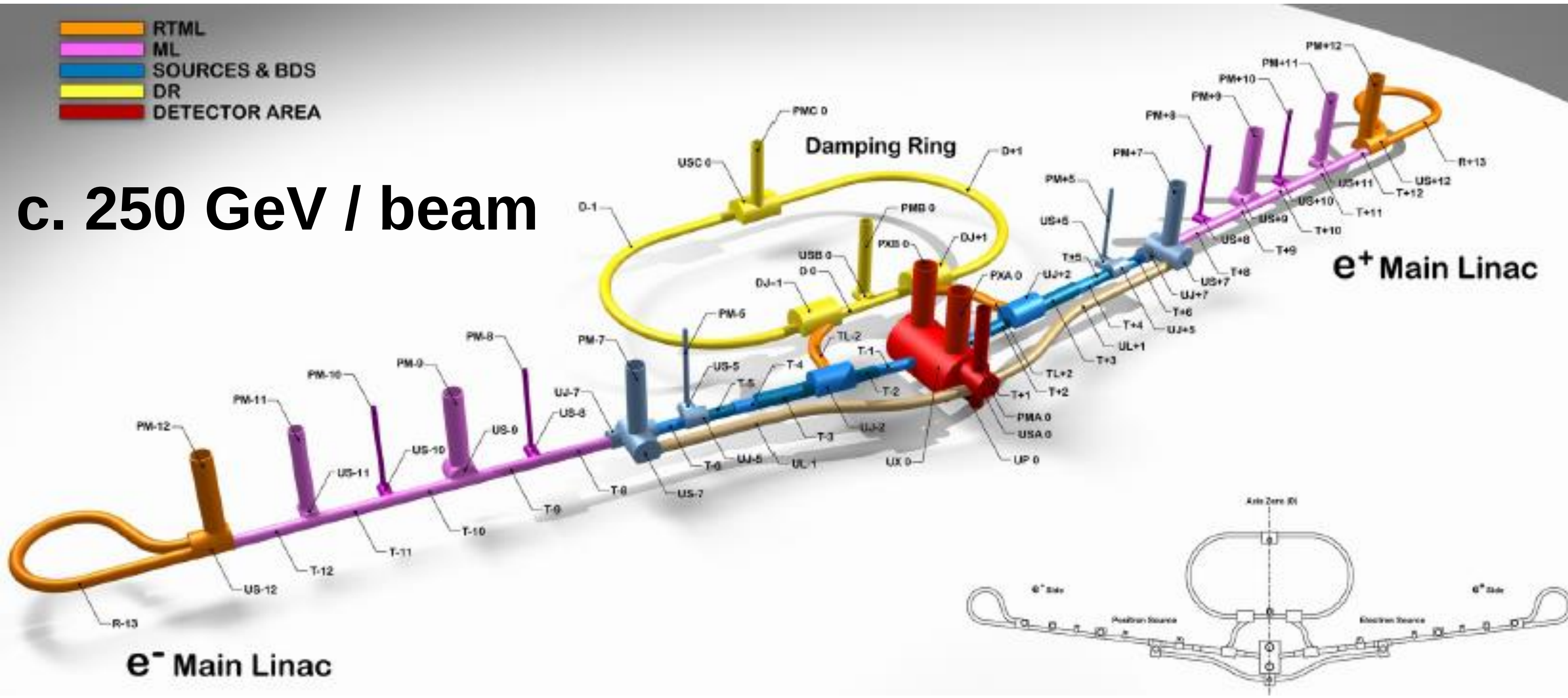
- ILC + CLIC luminosity requirements
- Interaction-point beam collision feedbacks
- Feedback system prototyping at ATF/ATF2
- Summary

Compact Linear Collider (CLIC)



1.5 TeV / beam

International Linear Collider (ILC)



c. 250 GeV / beam

31 km

LC beam parameters

	ILC 500	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	474	40	nm
Vertical IP beam size	6	1	nm
Longitudinal IP beam size	300	44	um
Luminosity	2	6	10**34

LC beam parameters

	ILC 500	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	474	40	nm
Vertical IP beam size	6	1	nm
Longitudinal IP beam size	300	44	um
Luminosity	2	6	10**34

LC beam parameters

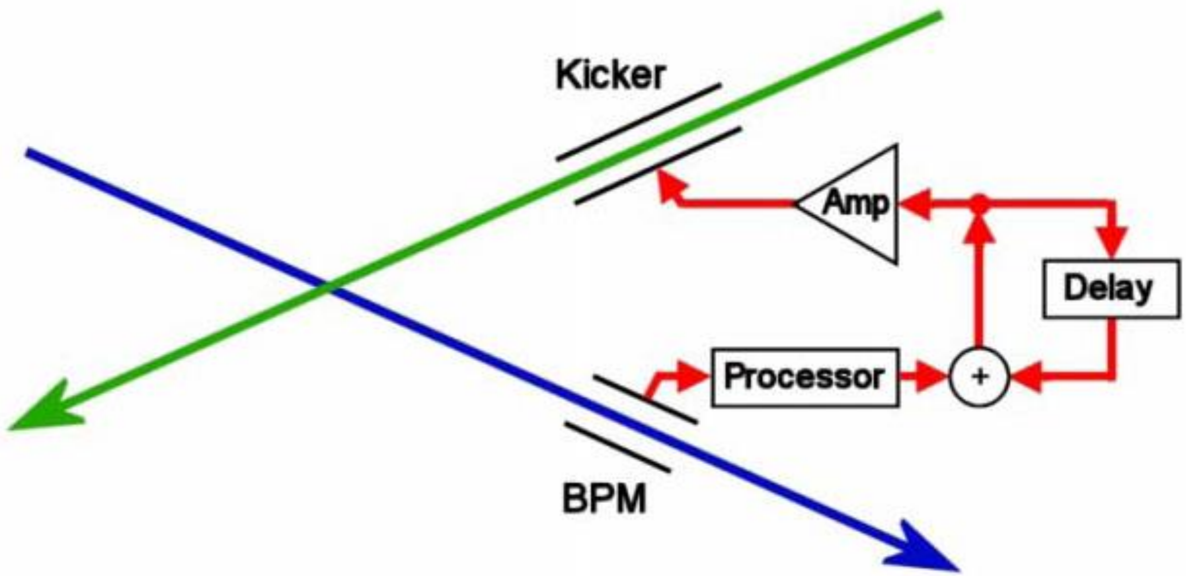
	ILC 500	CLIC 3 TeV	
Electrons/bunch	2	0.37	10**10
Bunches/train	1312	312	
Bunch separation	554	0.5	ns
Train length	727	0.156	us
Train repetition rate	5	50	Hz
Horizontal IP beam size	474	40	nm
Vertical IP beam size	6	1	nm
Longitudinal IP beam size	300	44	um
Luminosity	2	6	10**34

LC beam parameters

	ILC 500	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	474	40	nm
Vertical IP beam size	6	1	nm
Longitudinal IP beam size	300	44	um
Luminosity	2	6	10**34

LC 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, Christina Swinson

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

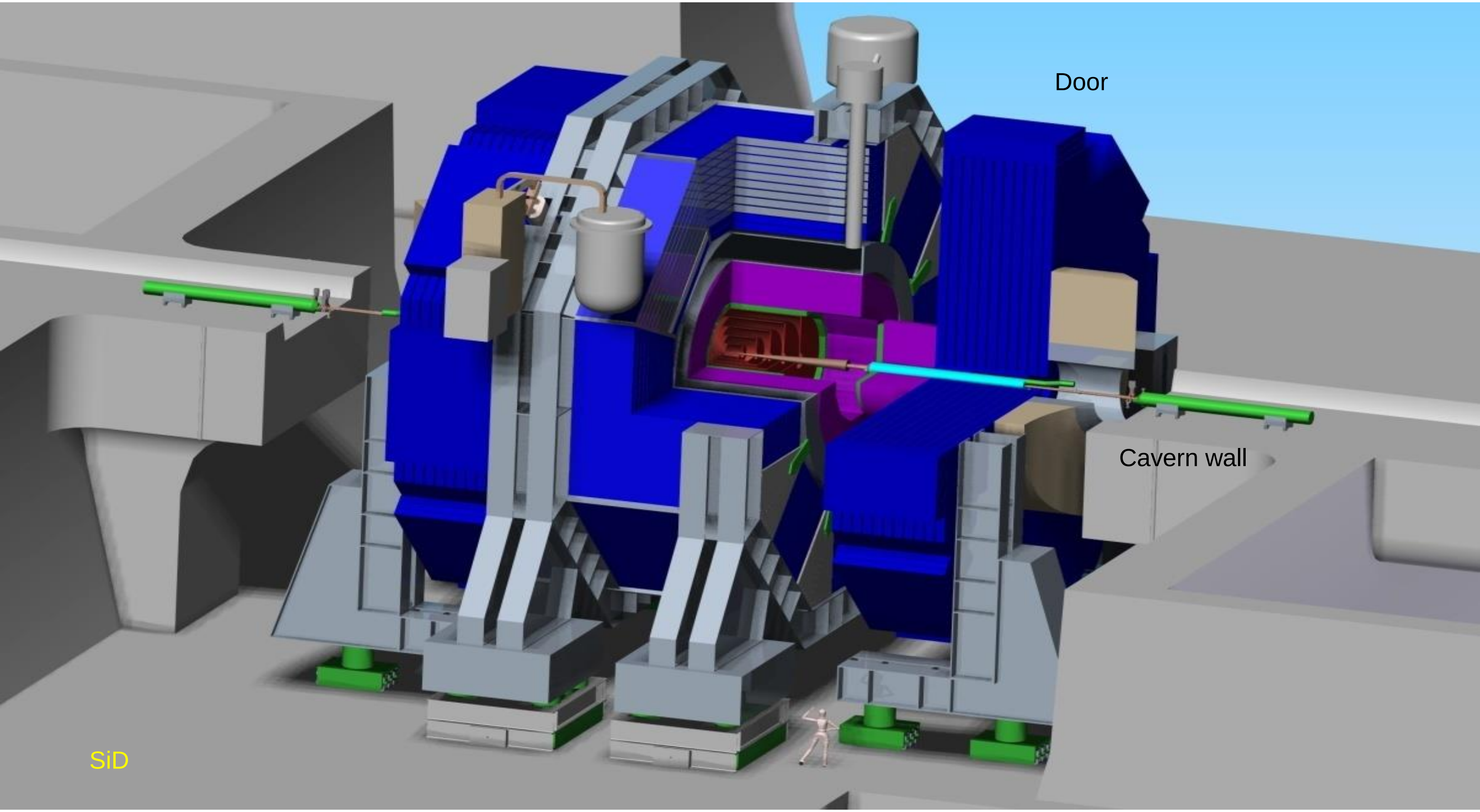
CLIC: O(10ns) latency requires analogue approach

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

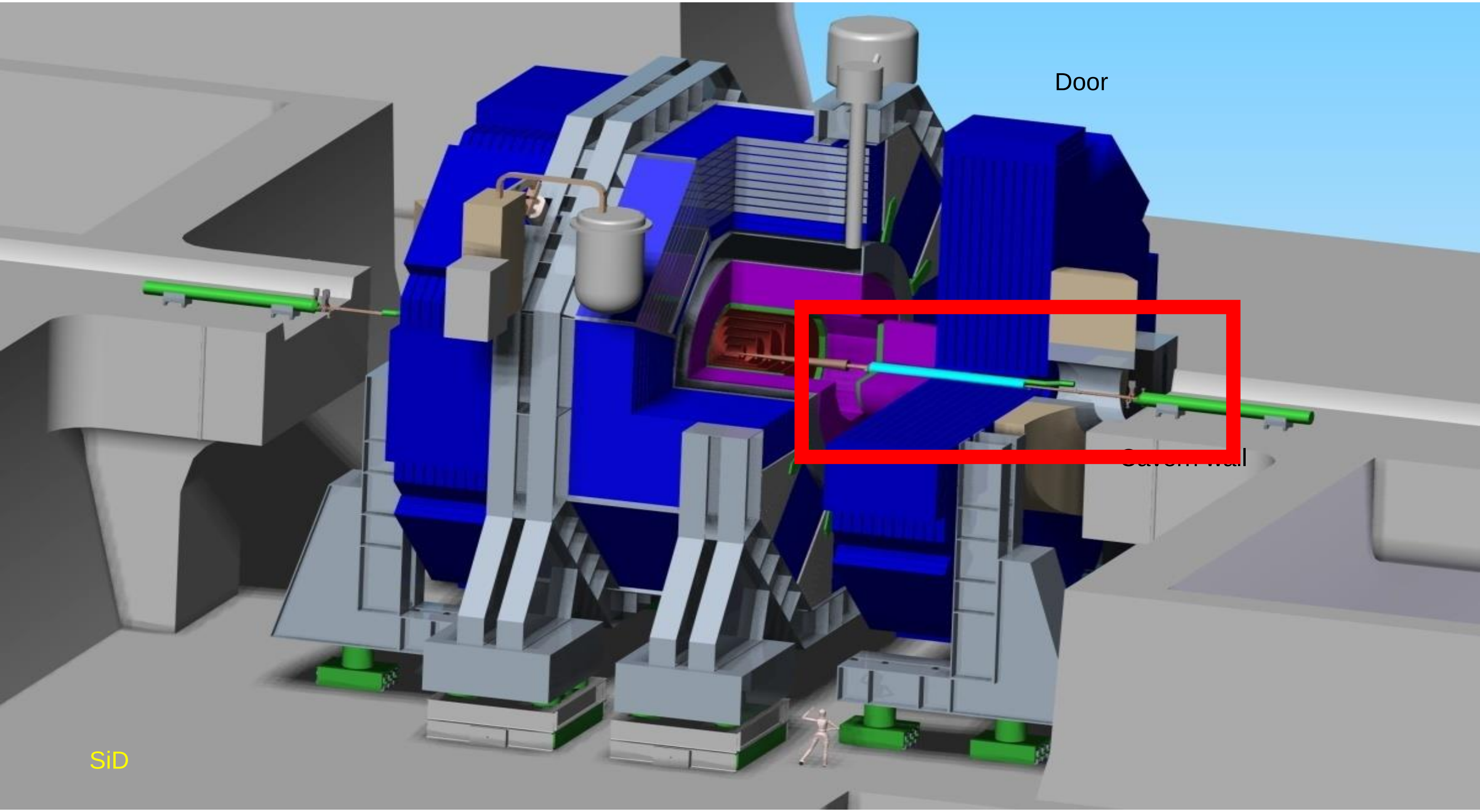
FB hardware should be close to IP (especially for CLIC!)

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

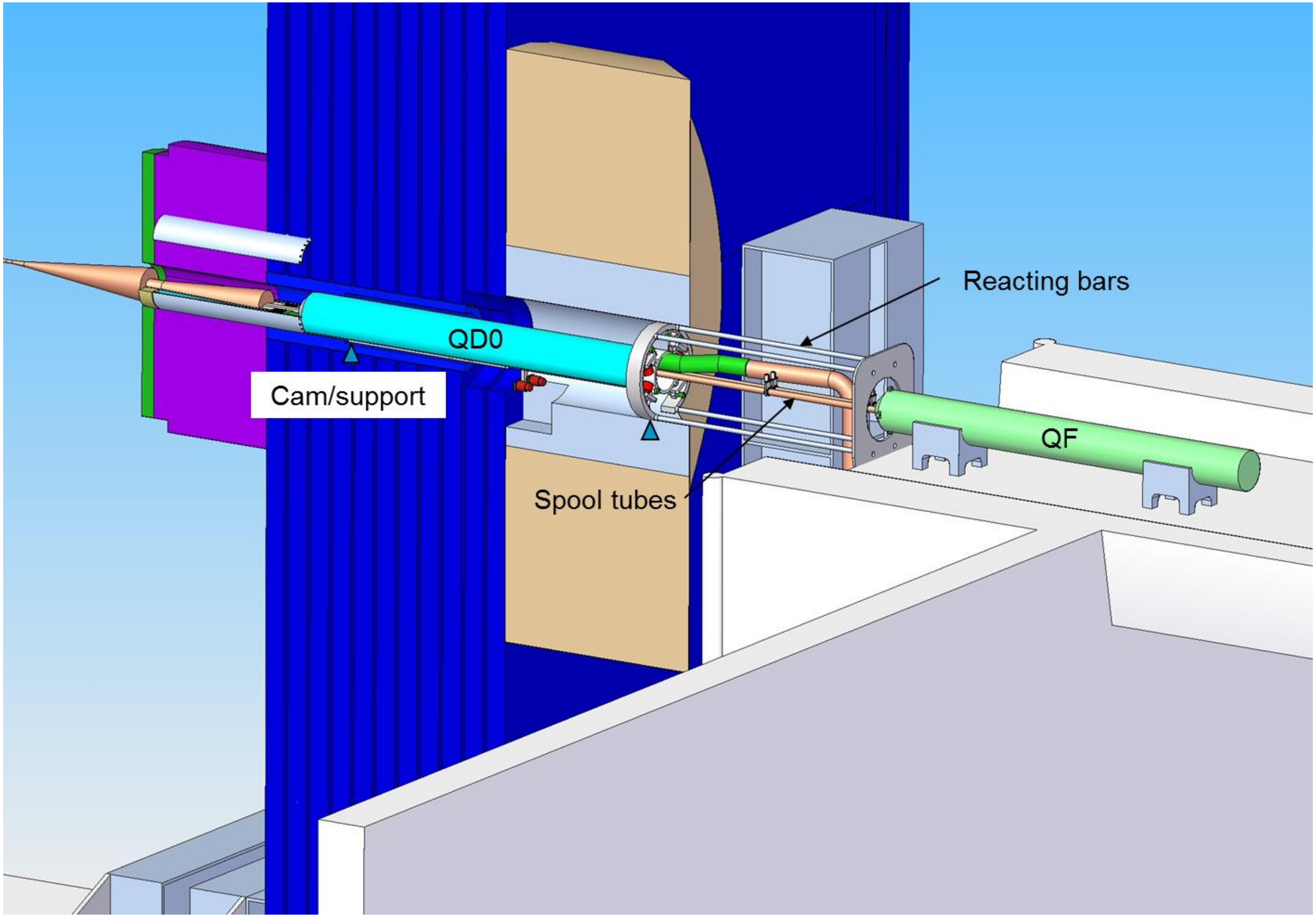
ILC IR: SiD for illustration



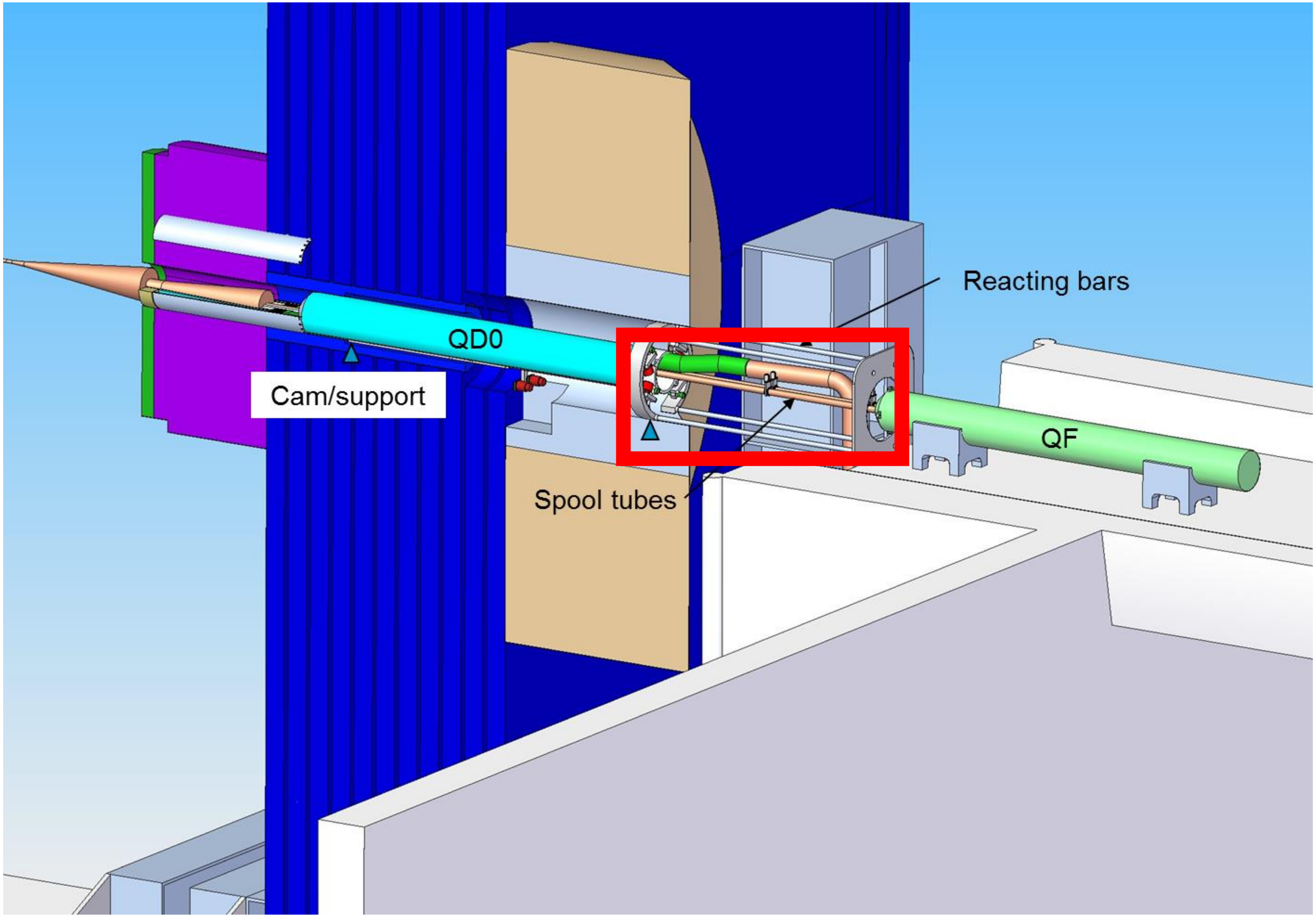
ILC IR: SiD for illustration



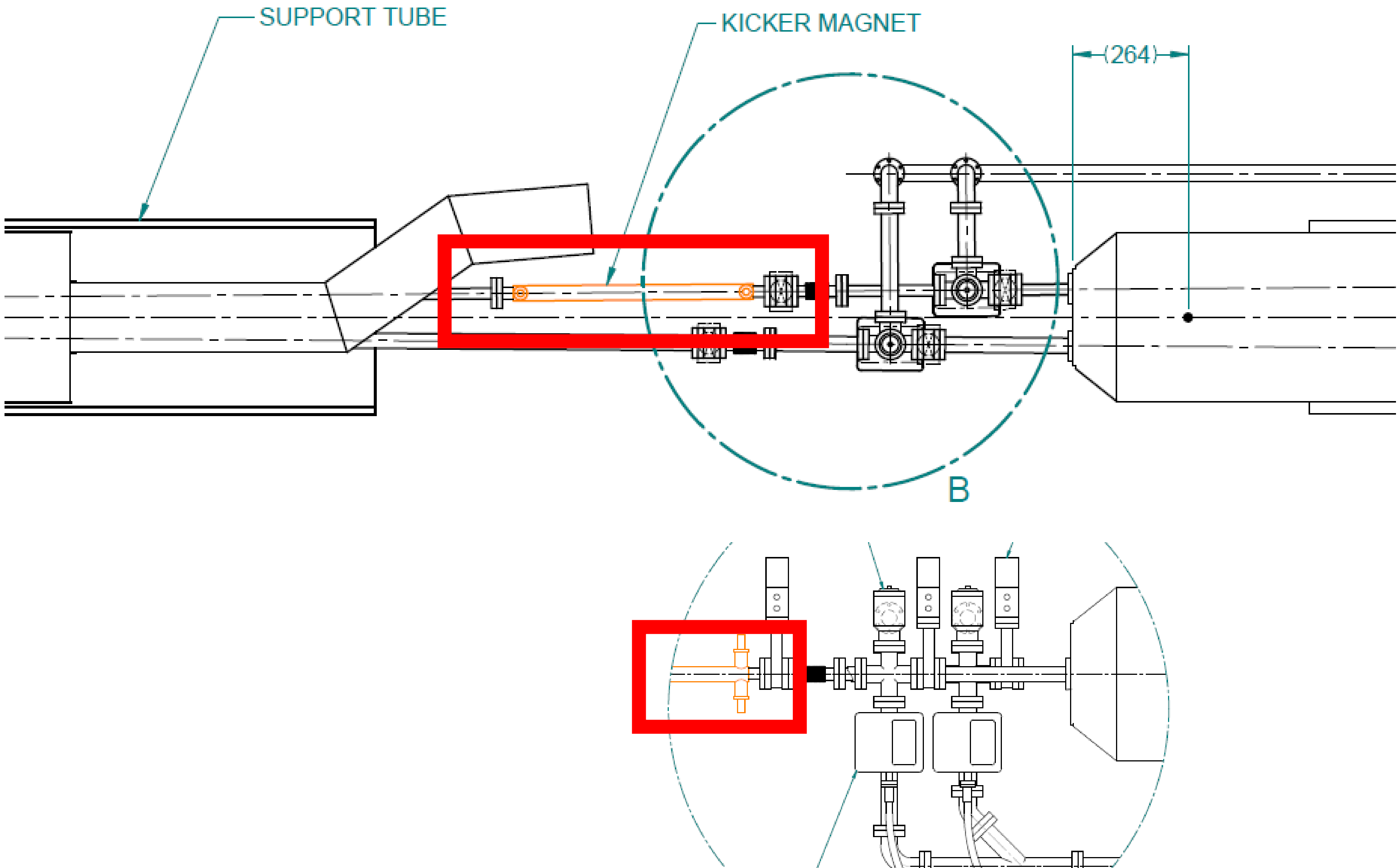
Final Doublet Region (SiD)



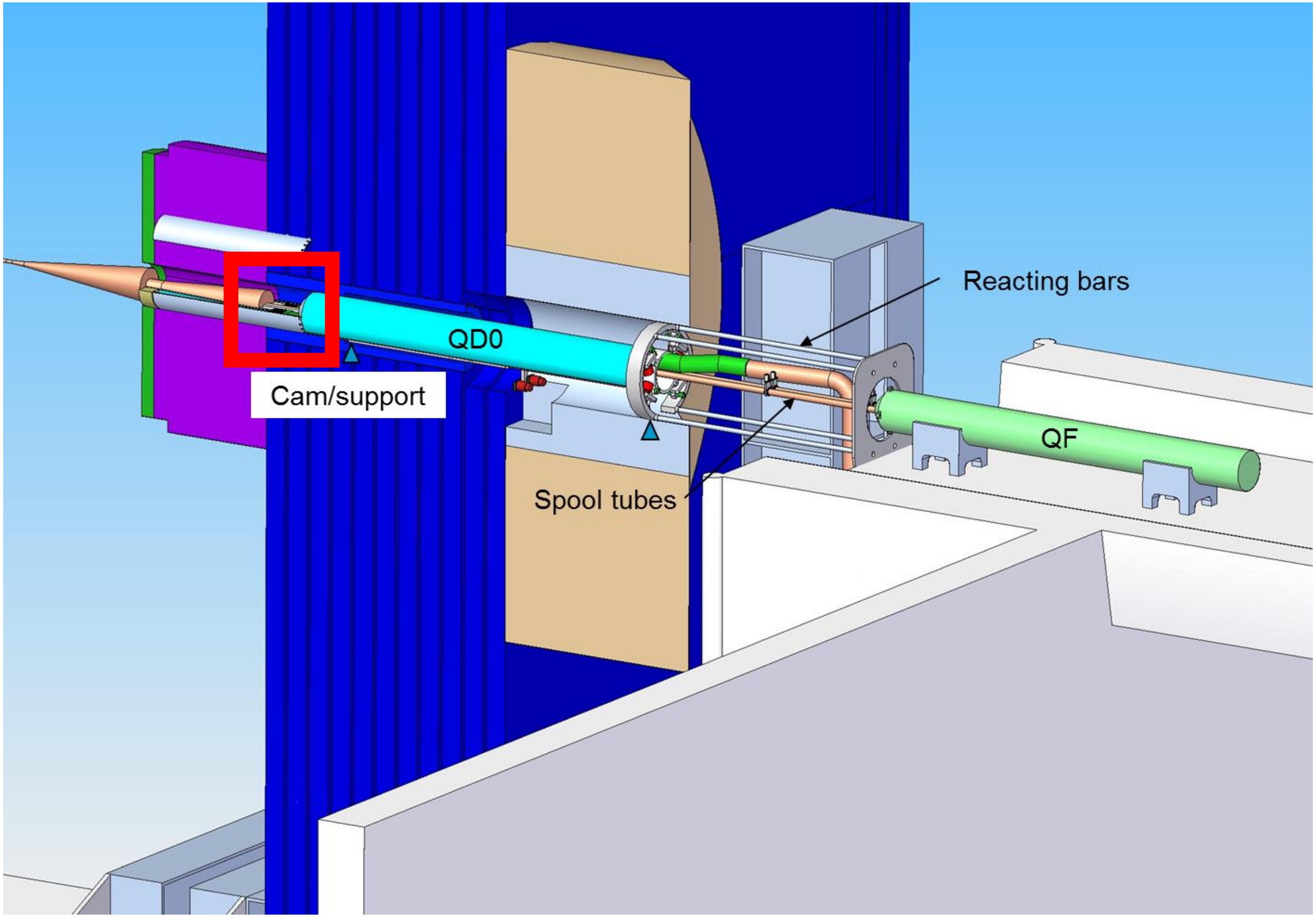
Final Doublet Region (SiD)



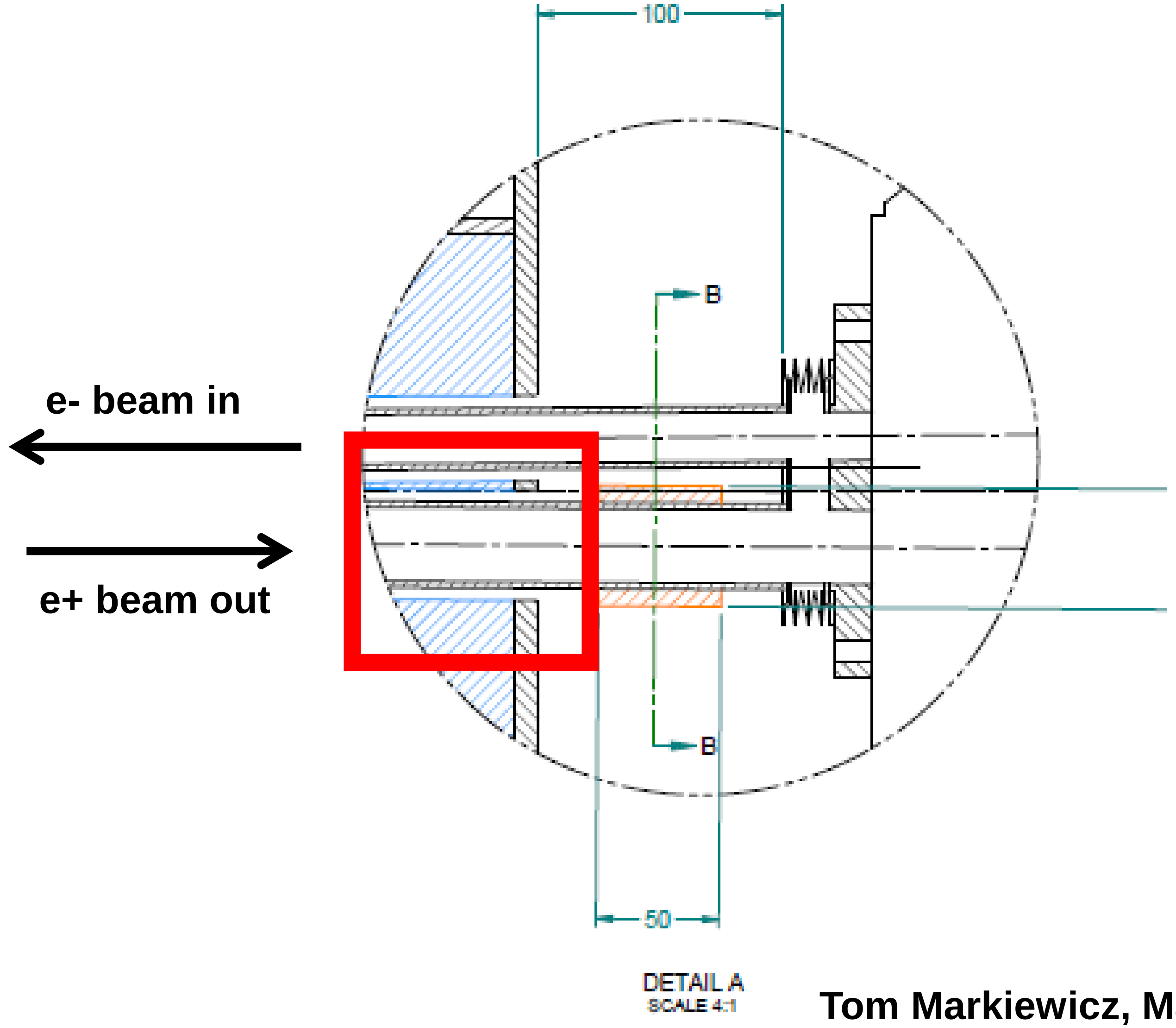
IP kicker detail (SiD)

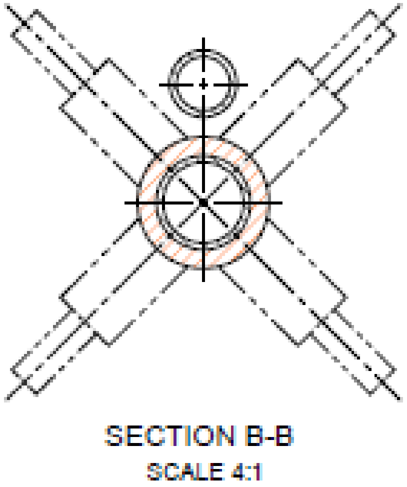


Final Doublet Region (SiD)



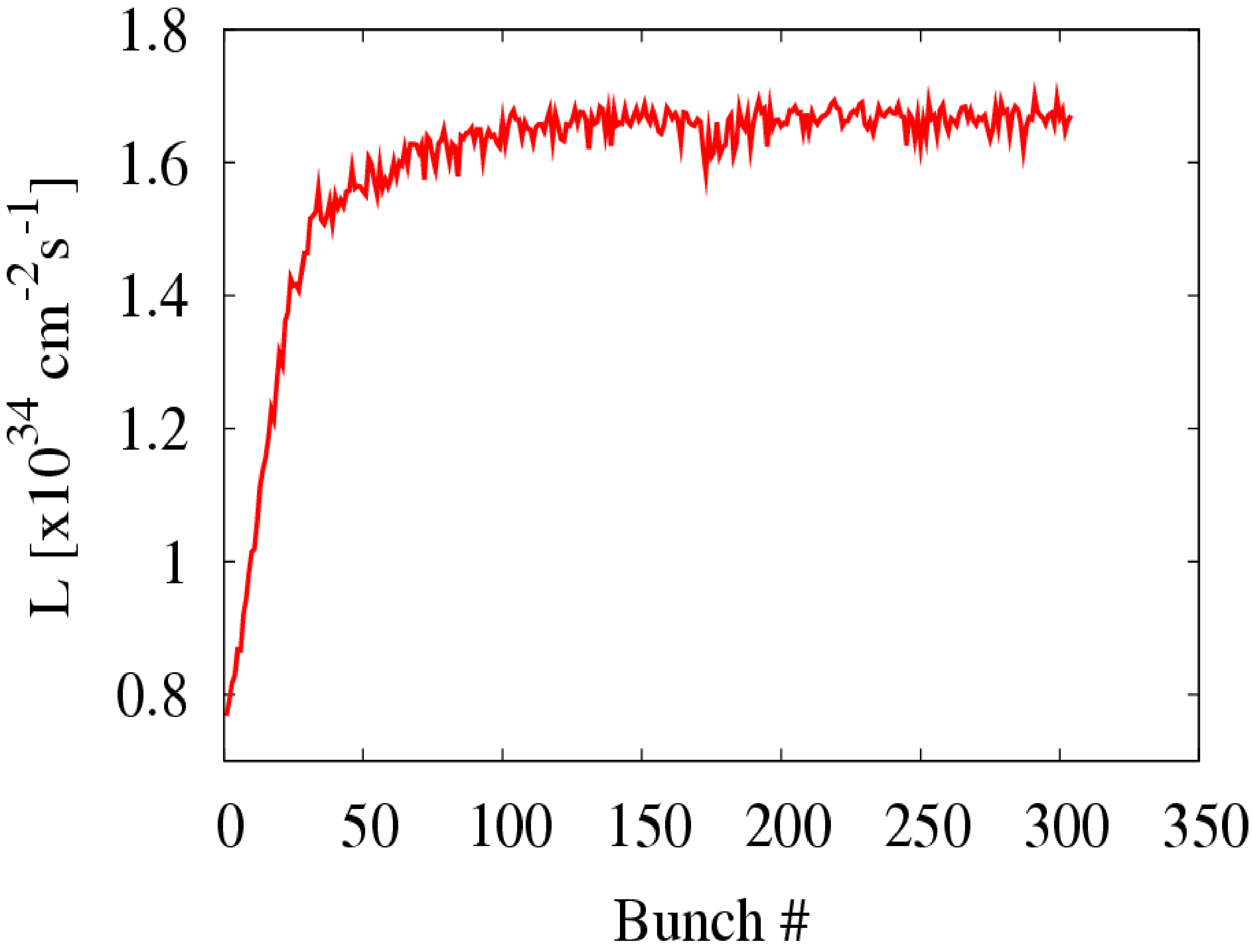
IP FB BPM detail (SiD)



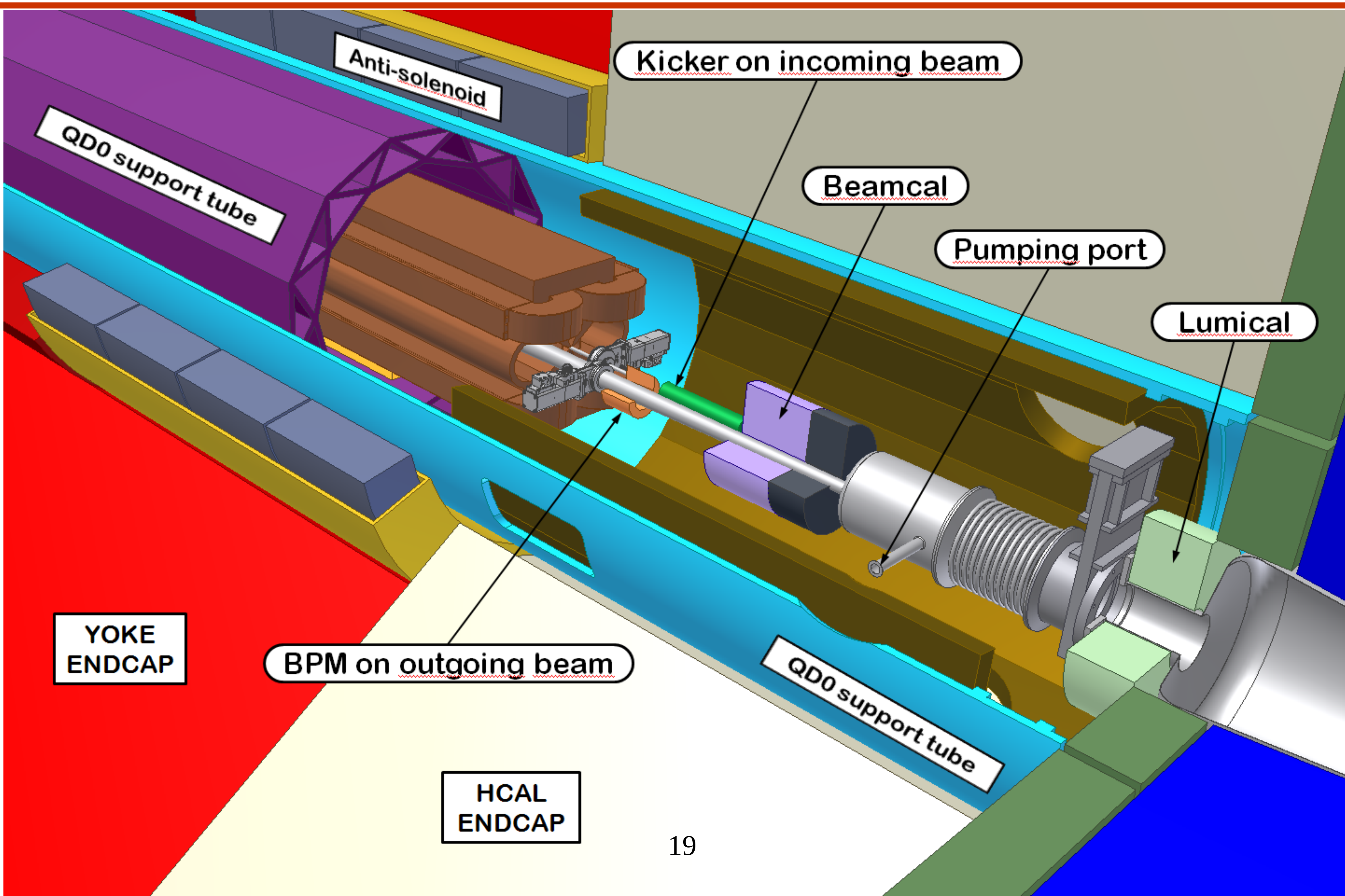


Tom Markiewicz, Marco Oriunno, Steve Smith

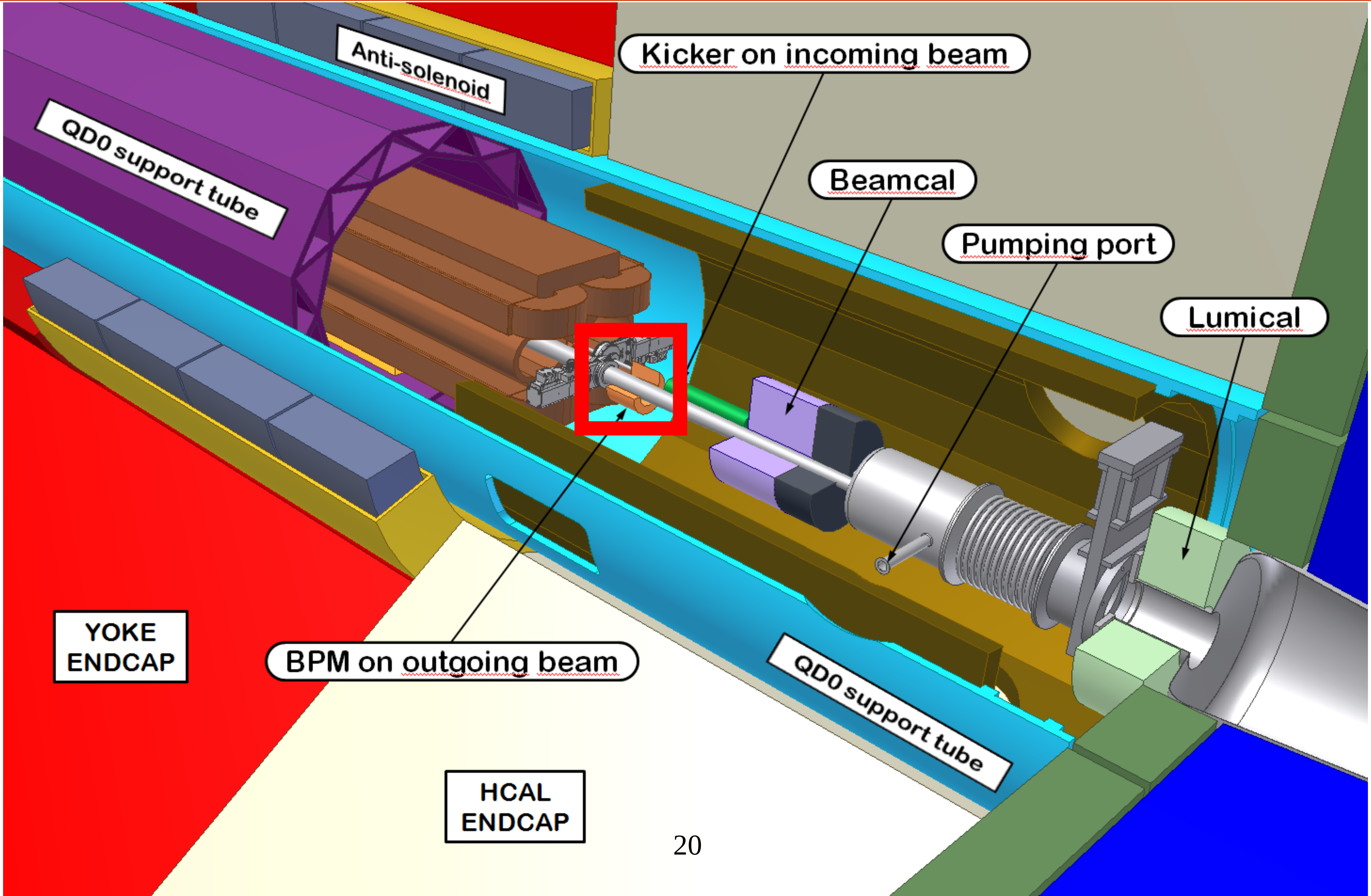
ILC IP FB performance (TDR)



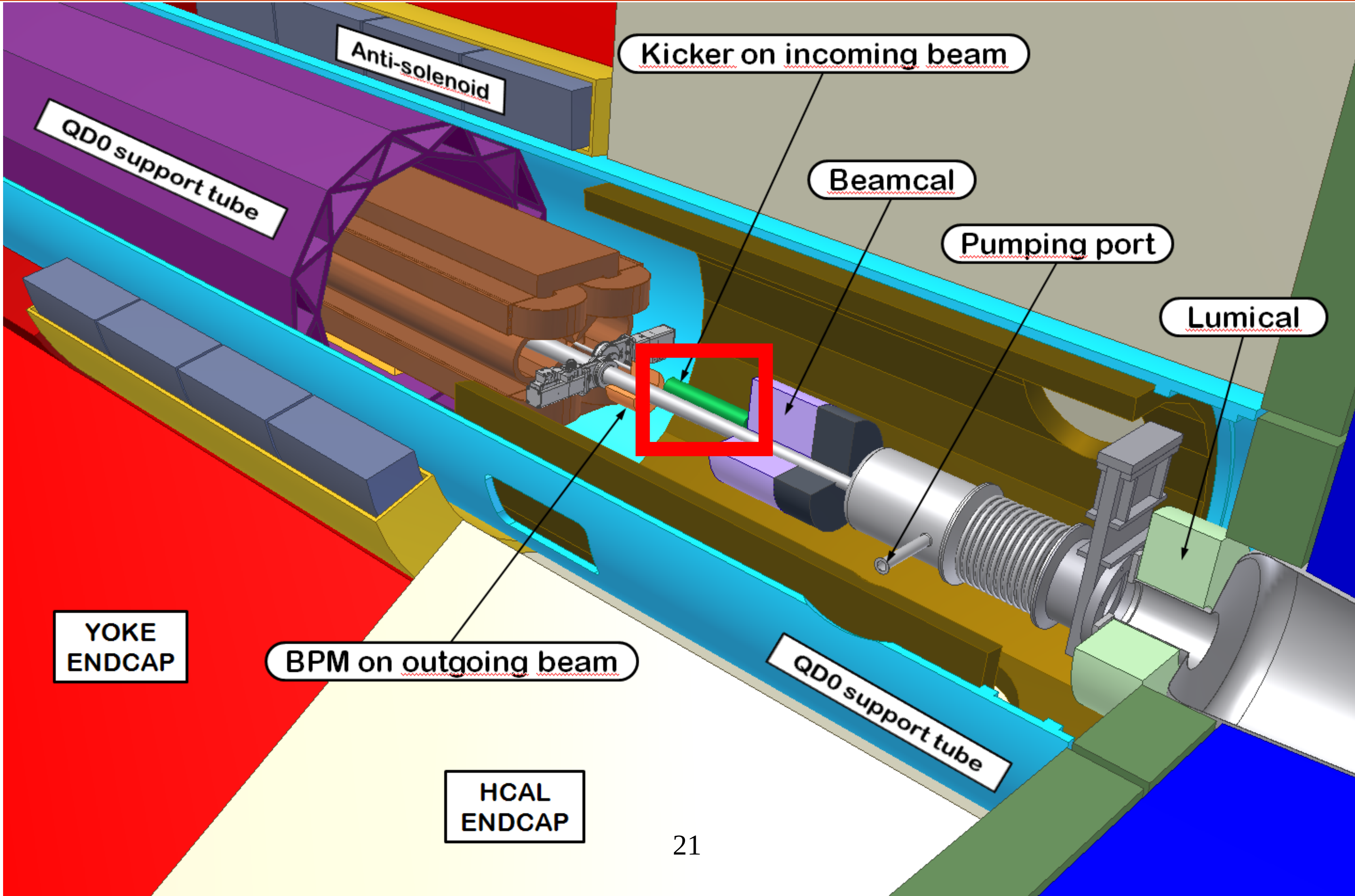
CLIC Final Doublet Region (CDR)



CLIC Final Doublet Region (CDR)

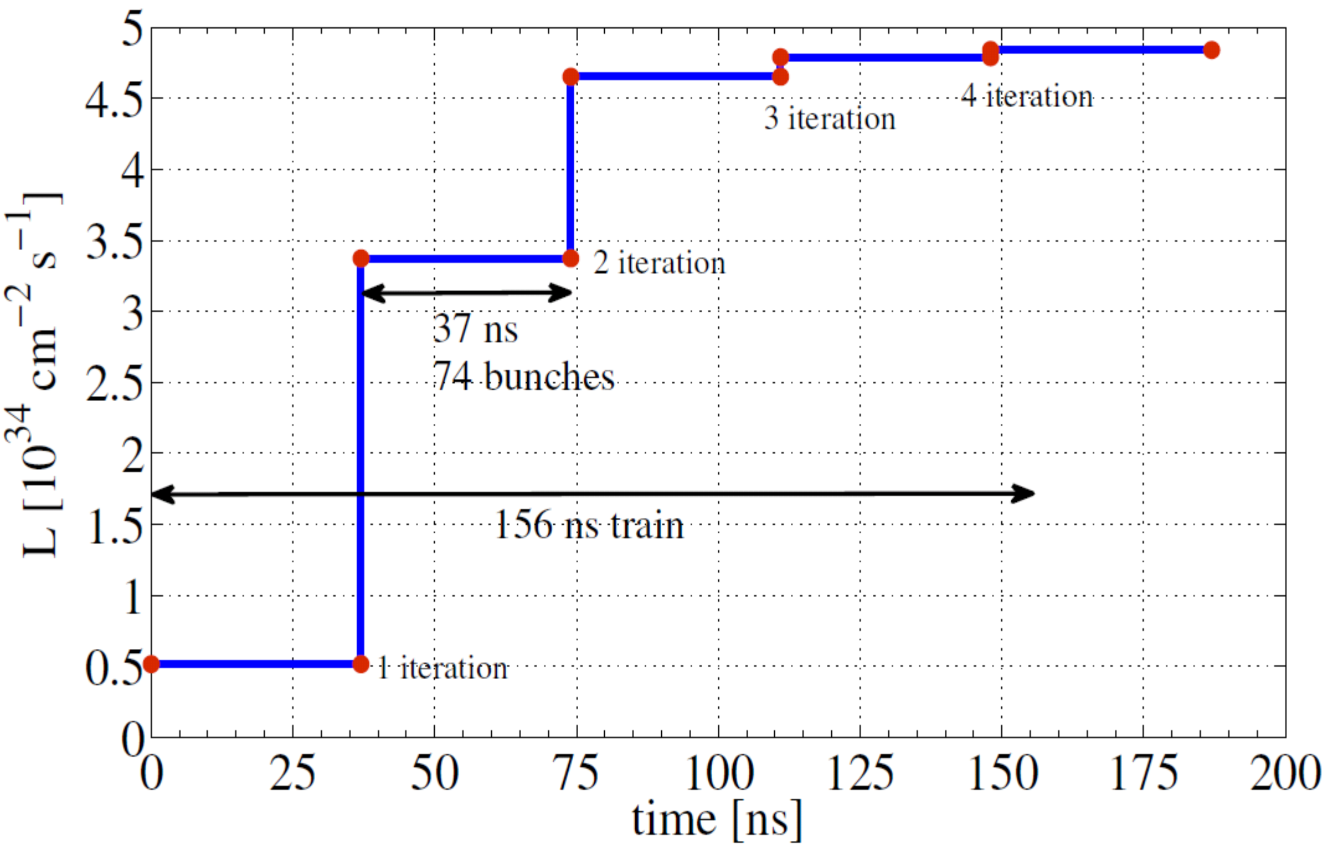


CLIC Final Doublet Region (CDR)

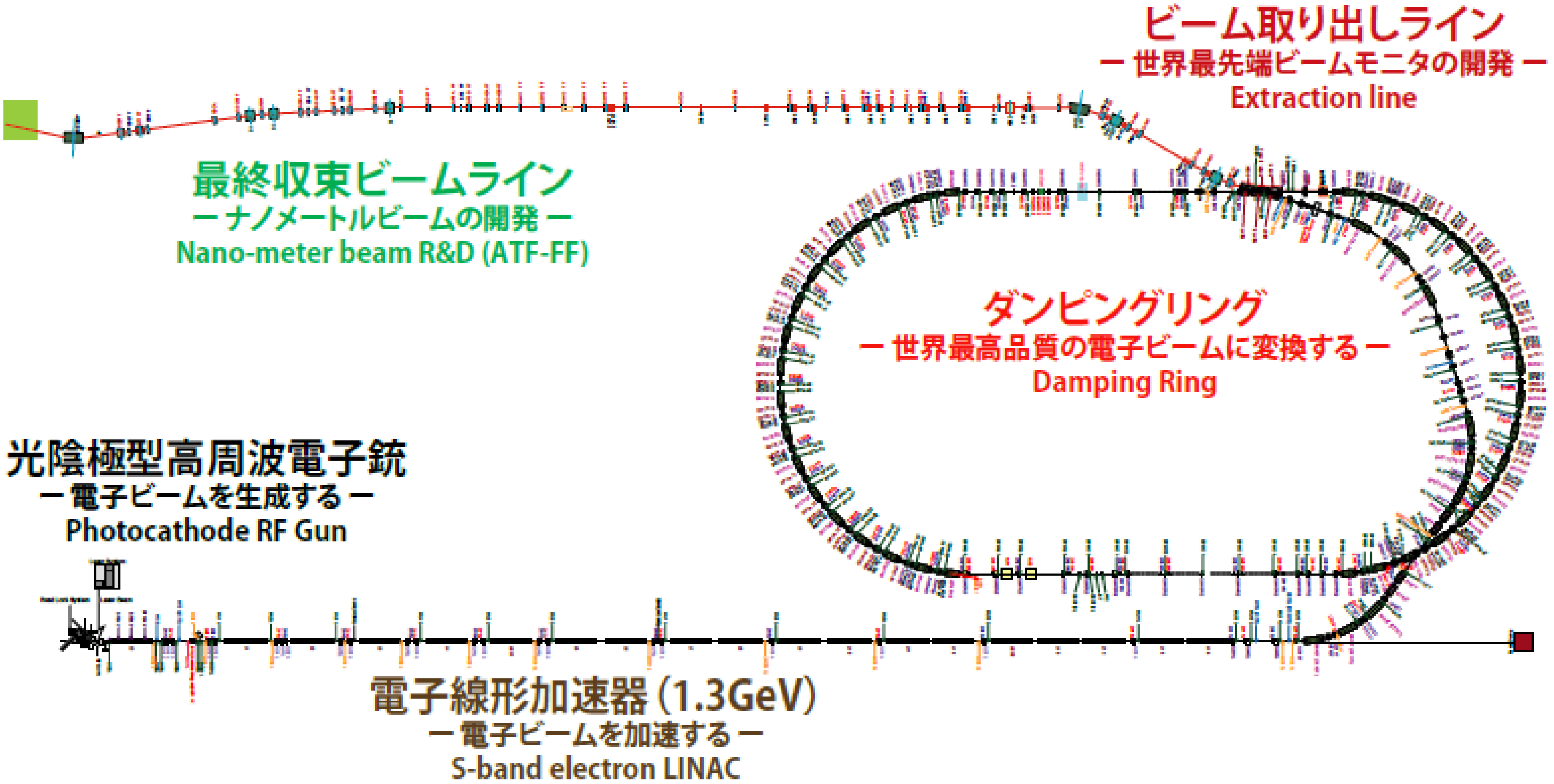


CLIC IP FB performance (CDR)

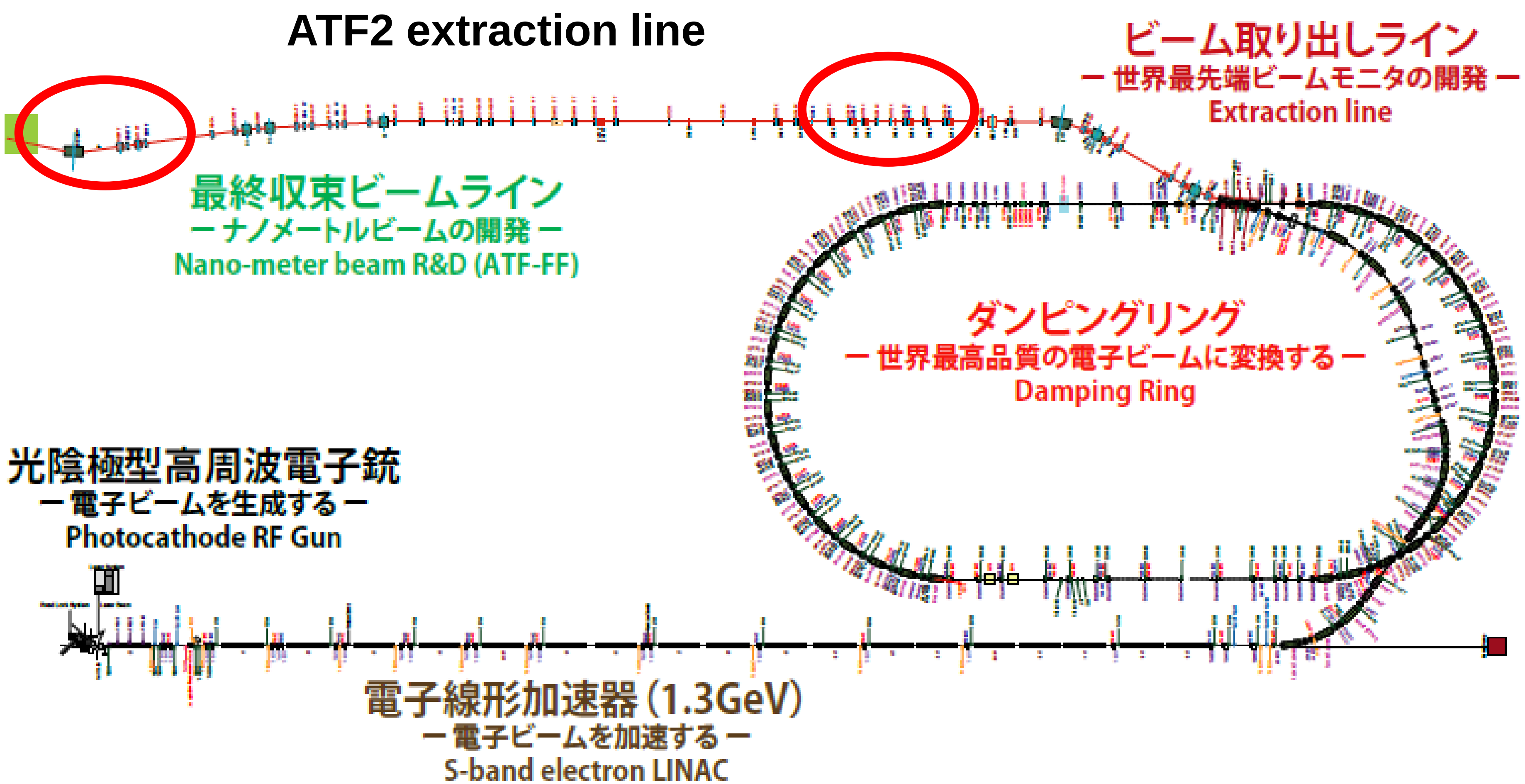
Single random seed of GM C



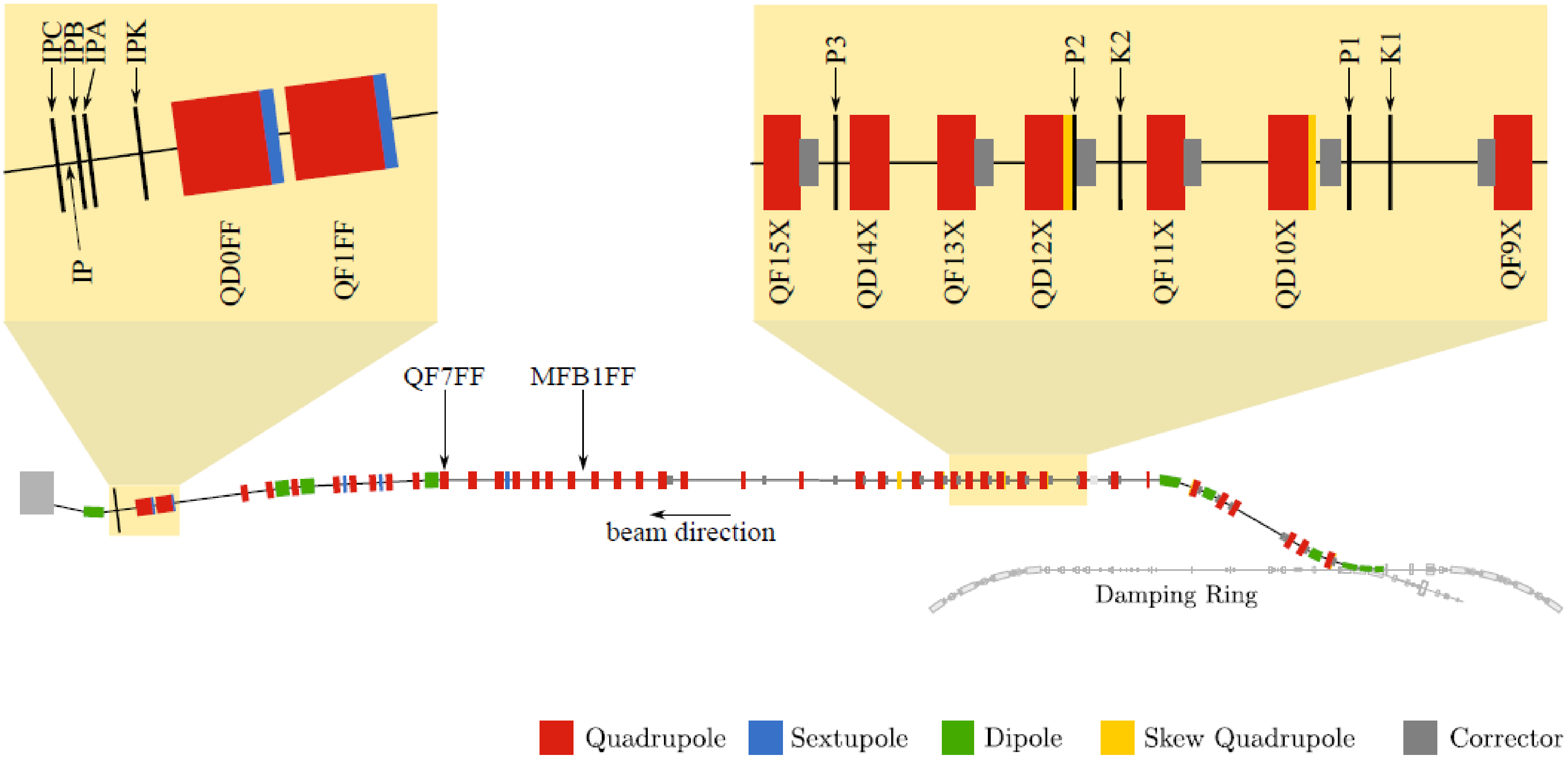
ATF2/KEK


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

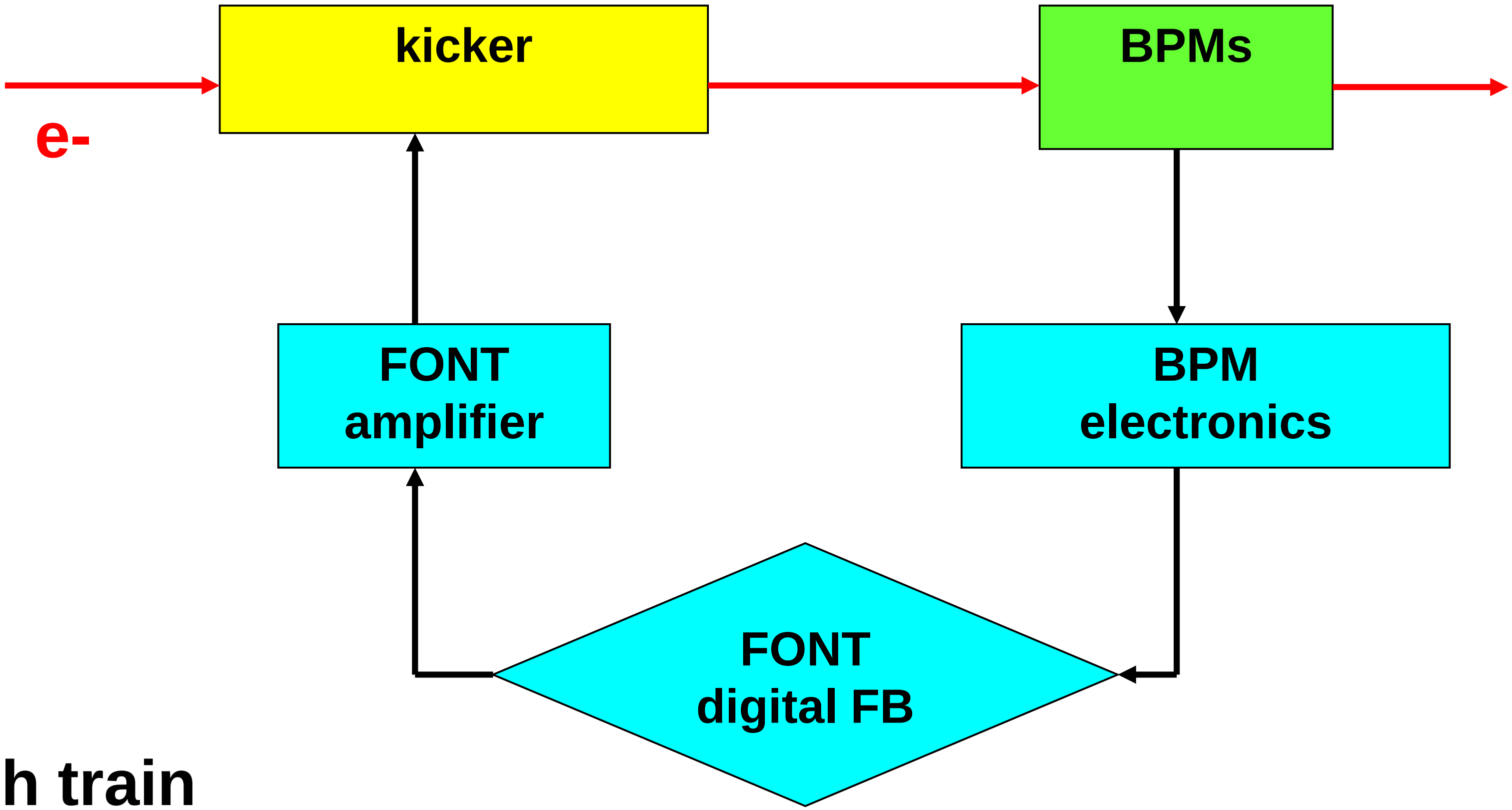
FONT5 ‘intra-train’ feedbacks



FONT5 ‘intra-train’ feedbacks



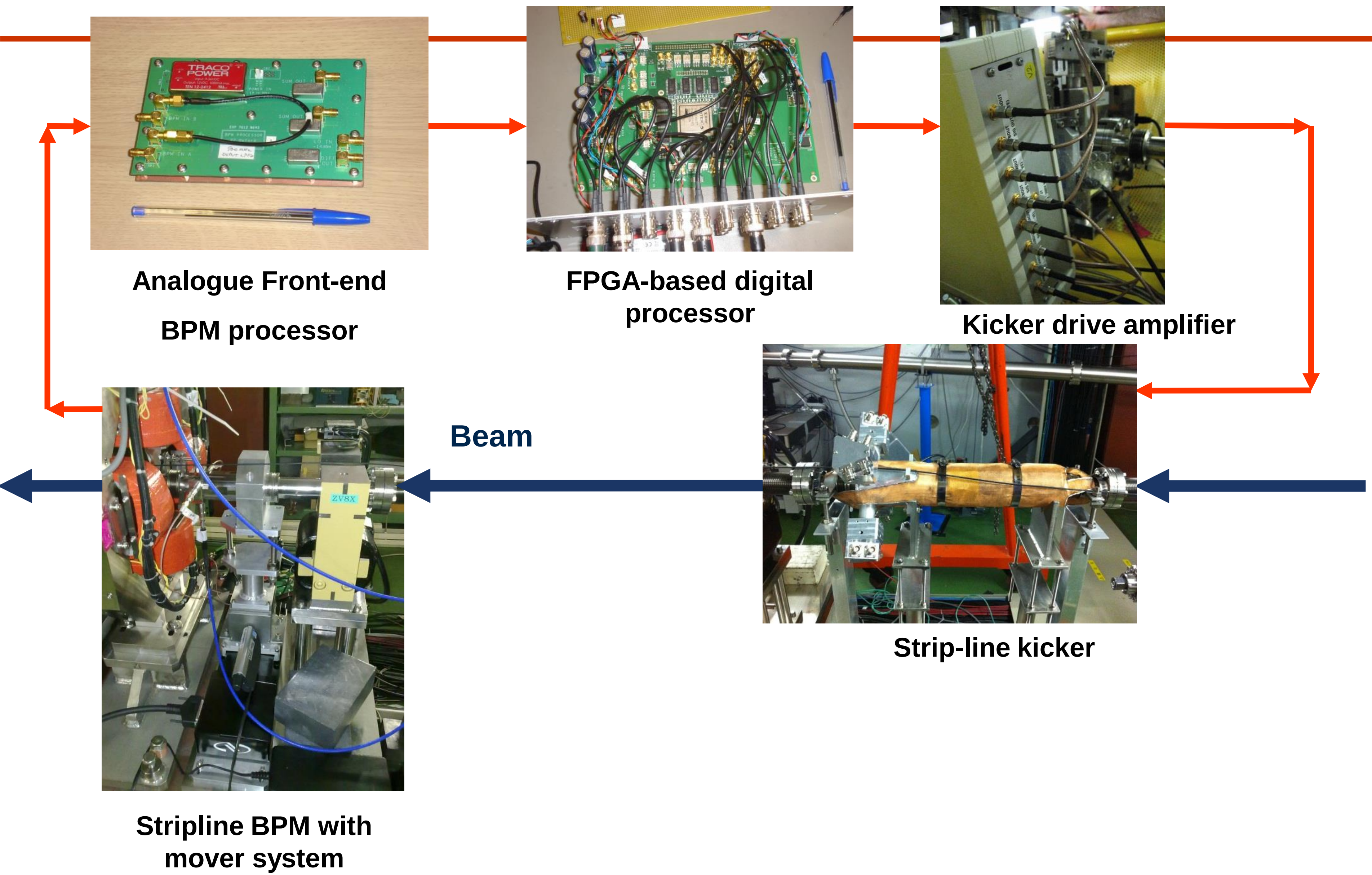
ILC-style IPFB loop schematic



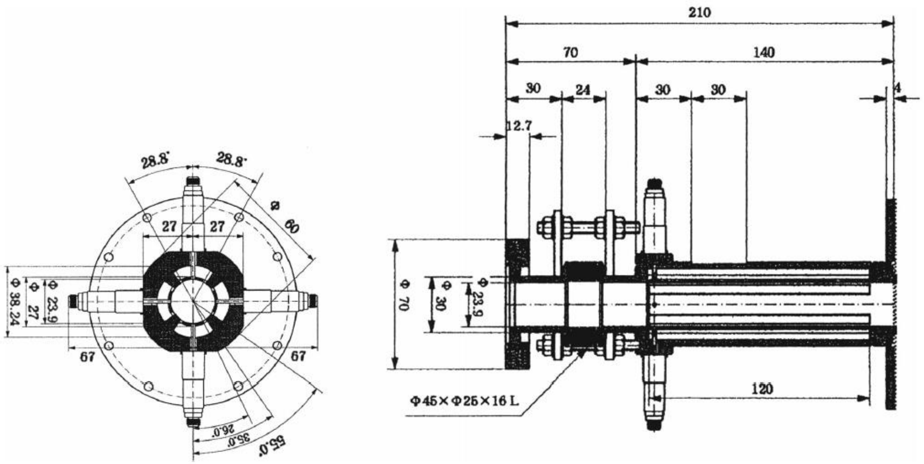
ATF2:

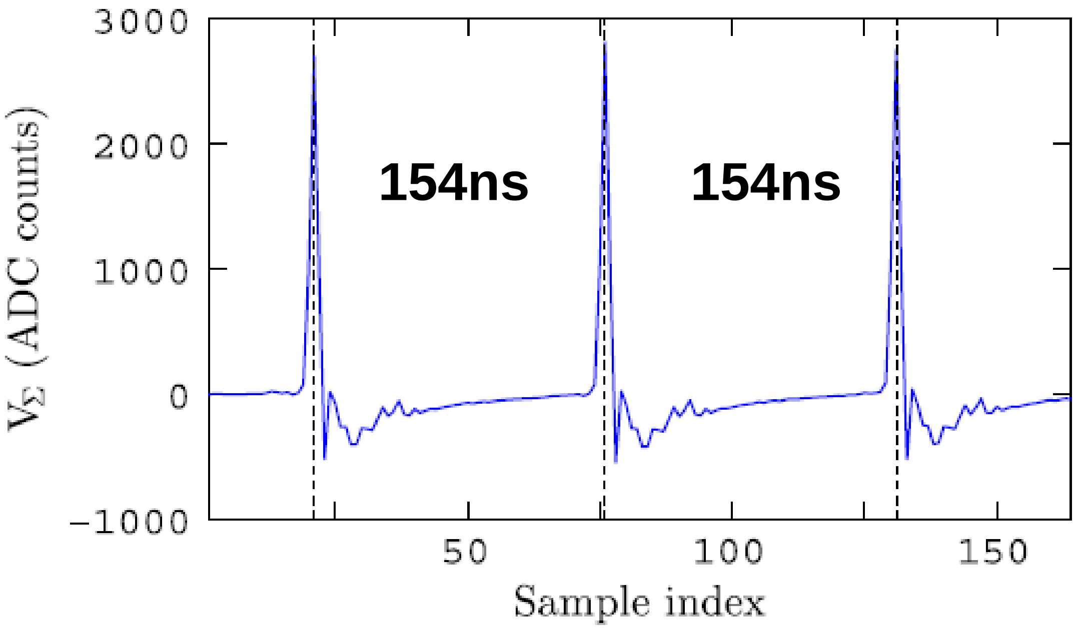
- 3-bunch train
- Bunch interval 154ns
- Measure bunch-1 vertical position
- Correct bunch-2 and bunch-3 positions

Upstream FONT5 System



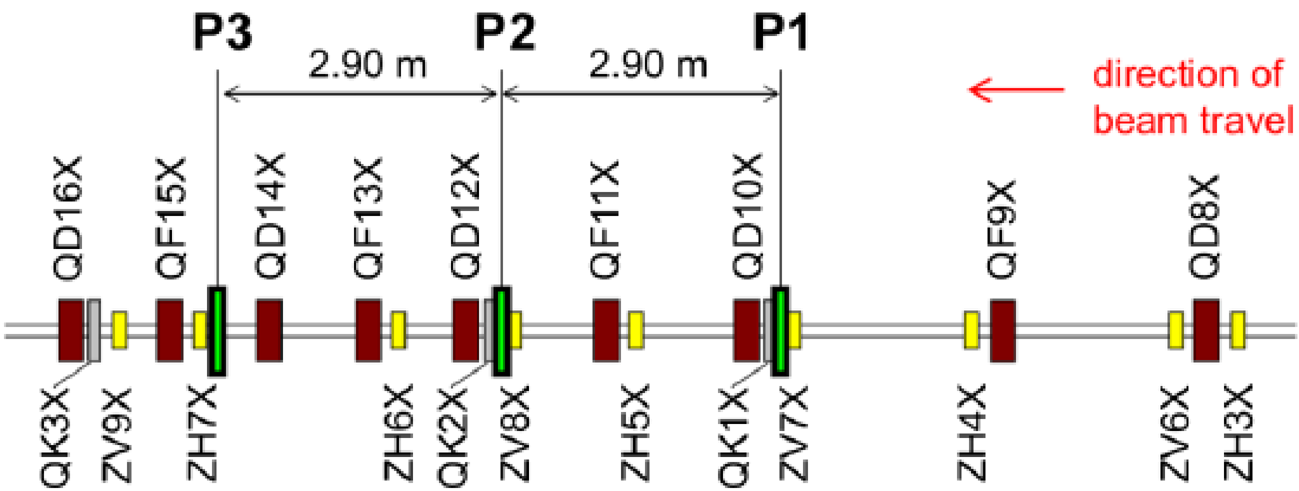
Stripline BPMs

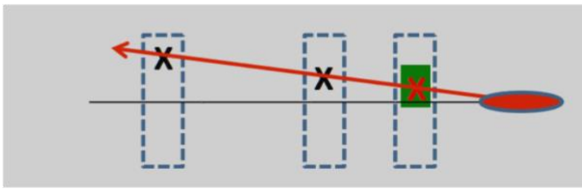




Excellent temporal resolution

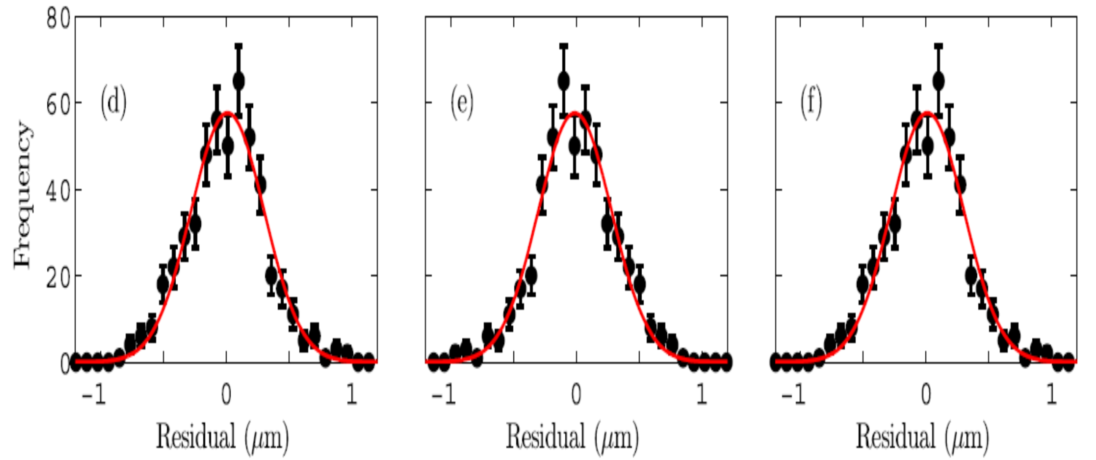
BPM spatial resolution





Resolution = 291 +- 10 nm (Q ~ 1nC),

→ meets ILC + CLIC requirements



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

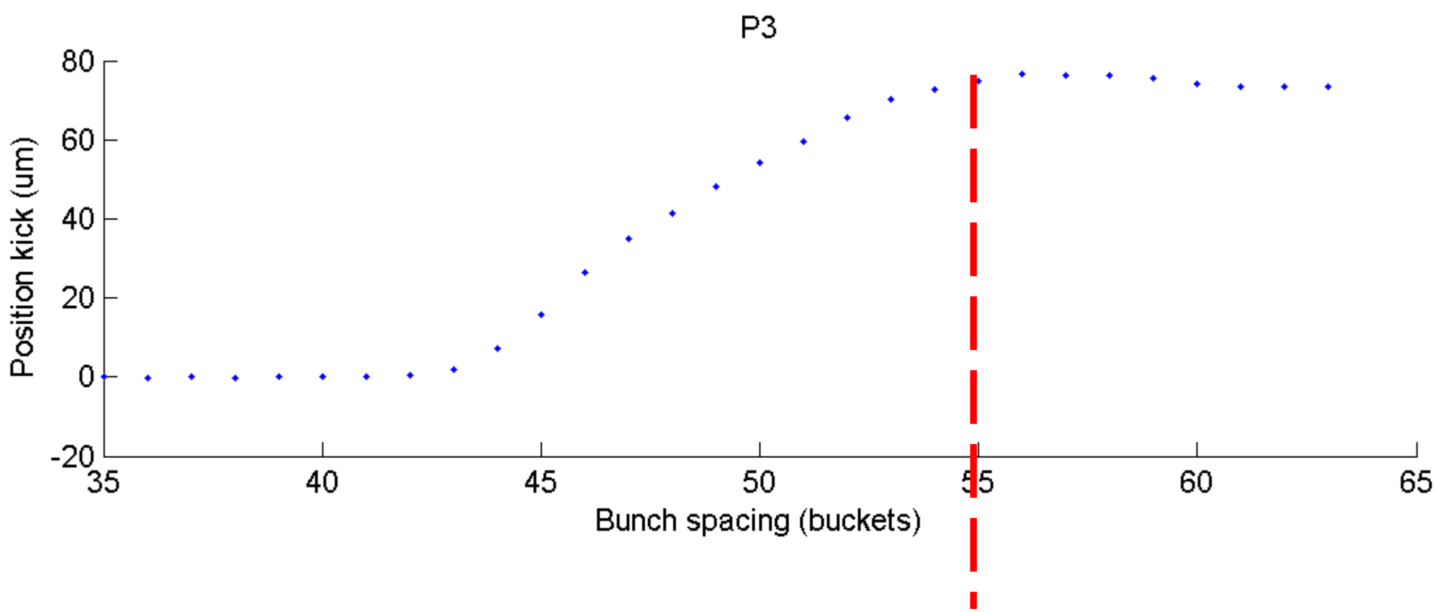
Design and performance of a high resolution, low latency stripline beam position monitor system

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

FB system latency

Kick to bunch 2

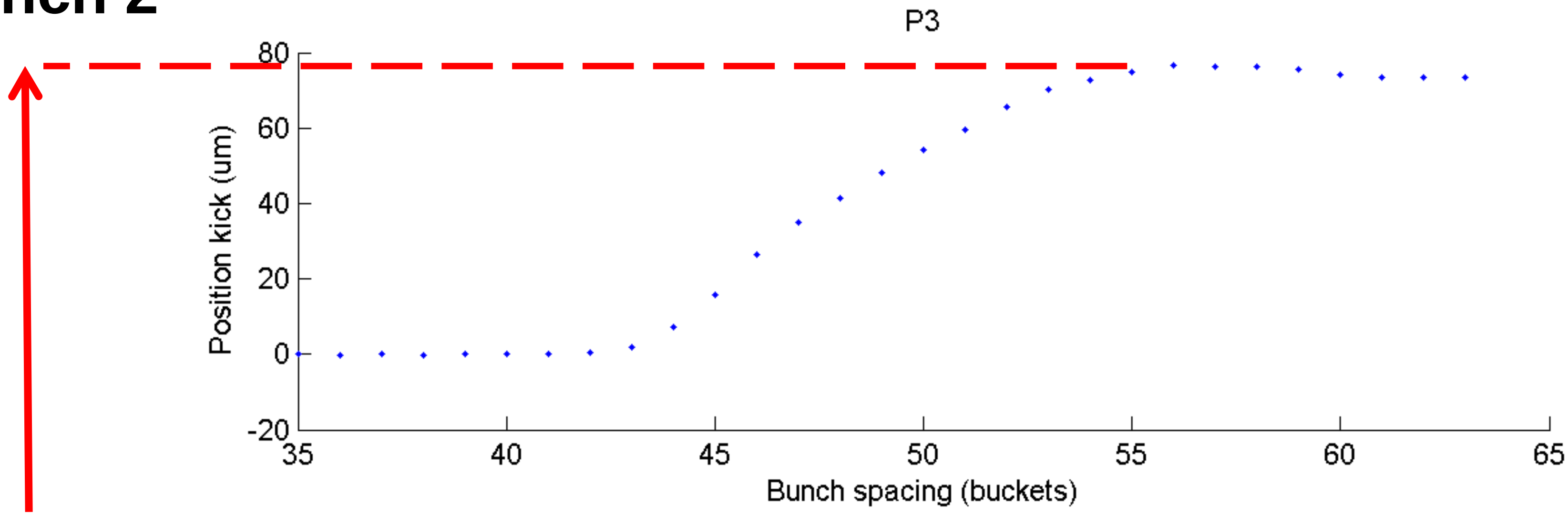


Latency: <154 ns

→ meets ILC requirements

FB system dynamic range

Kick to bunch 2



Max. kick = 75 um (1.3 GeV)

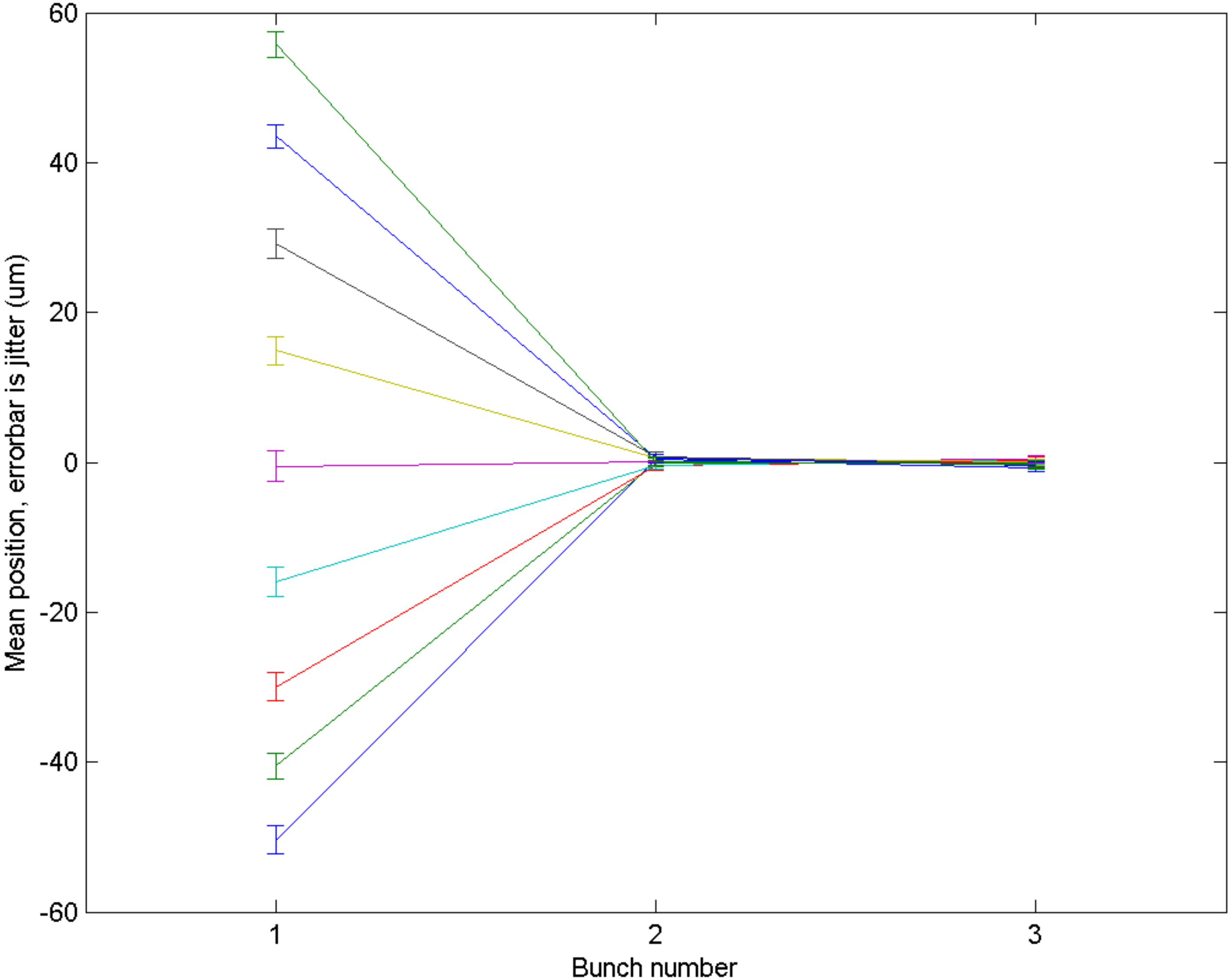
= 400 nm (ILC 250 GeV beam)

= 66 σ_y (ILC 250)

→ meets ILC requirement of 50 σ_y

Trajectory scan

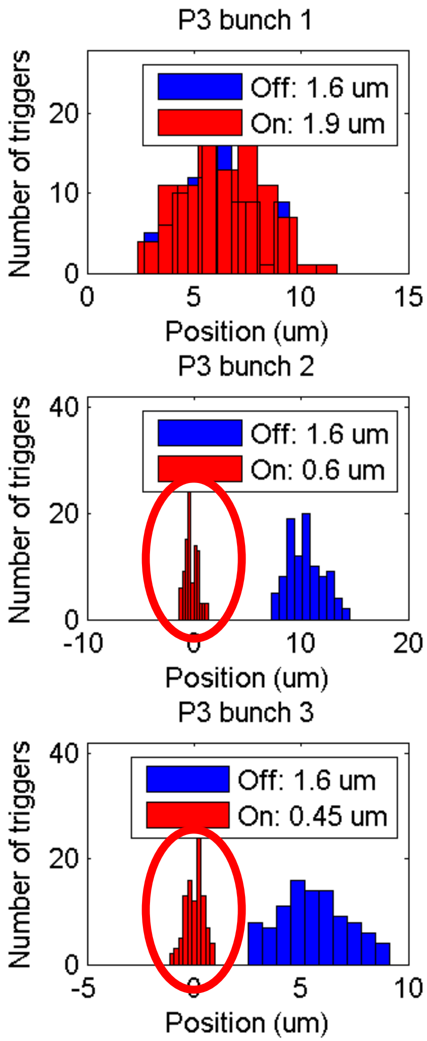
vertical beam position



Operational jitter correction

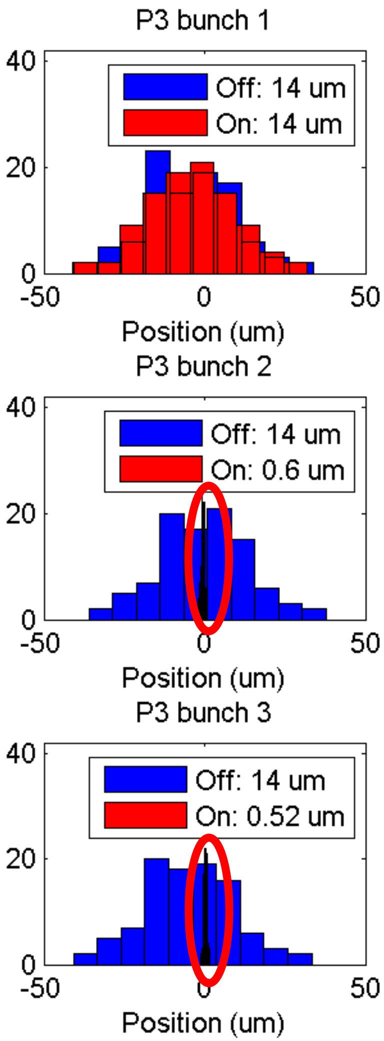
Normal operations:

2um jitter
→ 500nm



Deliberately enhanced jitter:

14um jitter
→ 500nm



Summary

- Advanced designs for intra-train beam feedbacks for ILC and CLIC
- Simulations show excellent potential to meet ILC + CLIC design luminosities
- Prototypes tested at ATF with multi-bunch beam
- Digital FB meets ILC requirements in terms of:

  BPM resolution

  system latency

  beam-correction dynamic range
- Routinely stabilise 1.3 GeV beam to sub-um level
- Applicable to single-pass e- beamlines eg. FELs

Summary – not presented

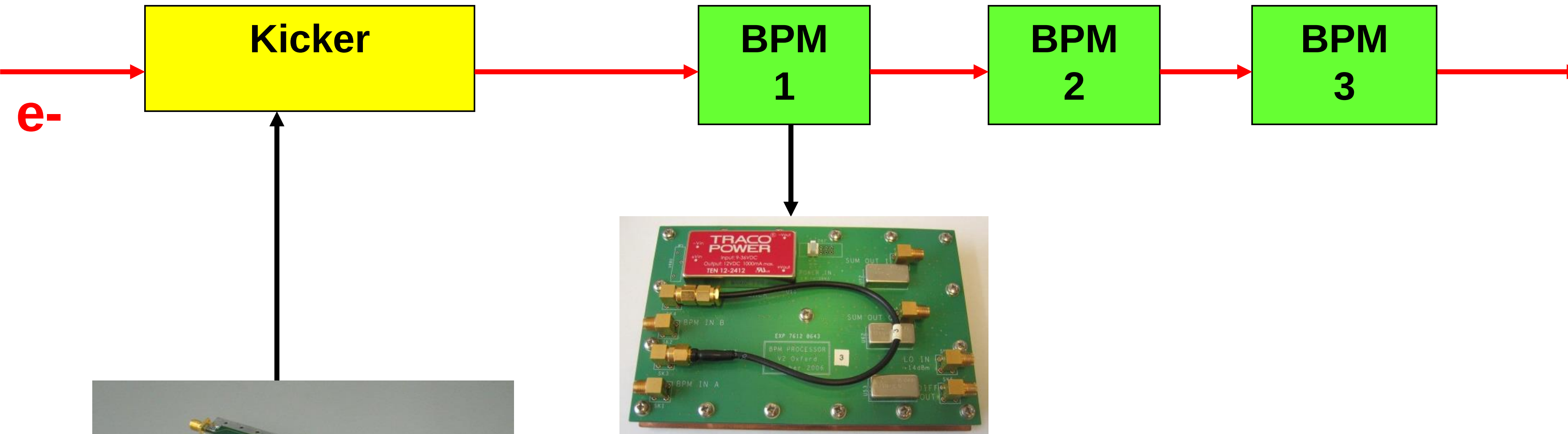
- **Tested all-analogue FB system that meets CLIC IP FB requirements for latency + drive**
- **ATF2 coupled-loop FB system for y + y’ correction**
  - **→ extrapolated performance ~ 4 nm at IP**
- **Single-beam ATF2 IP FB based on cavity BPMs**
  - **→ direct beam stabilisation < 70nm at IP**

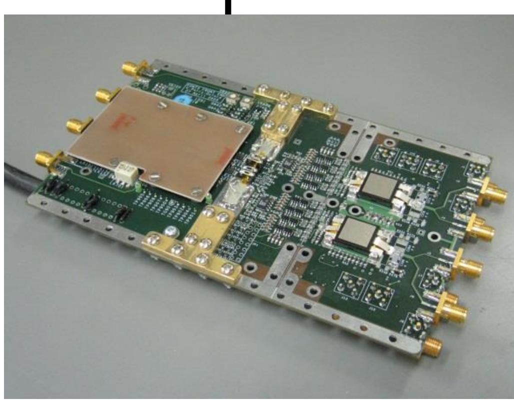
Issue at ATF2 is how to measure directly the beam position at nm level …

… not relevant for ILC+CLIC because beam-beam deflection provides O(100um) signal input to IP FB

Backup slides

CLIC prototype: FONT3 at KEK/ATF





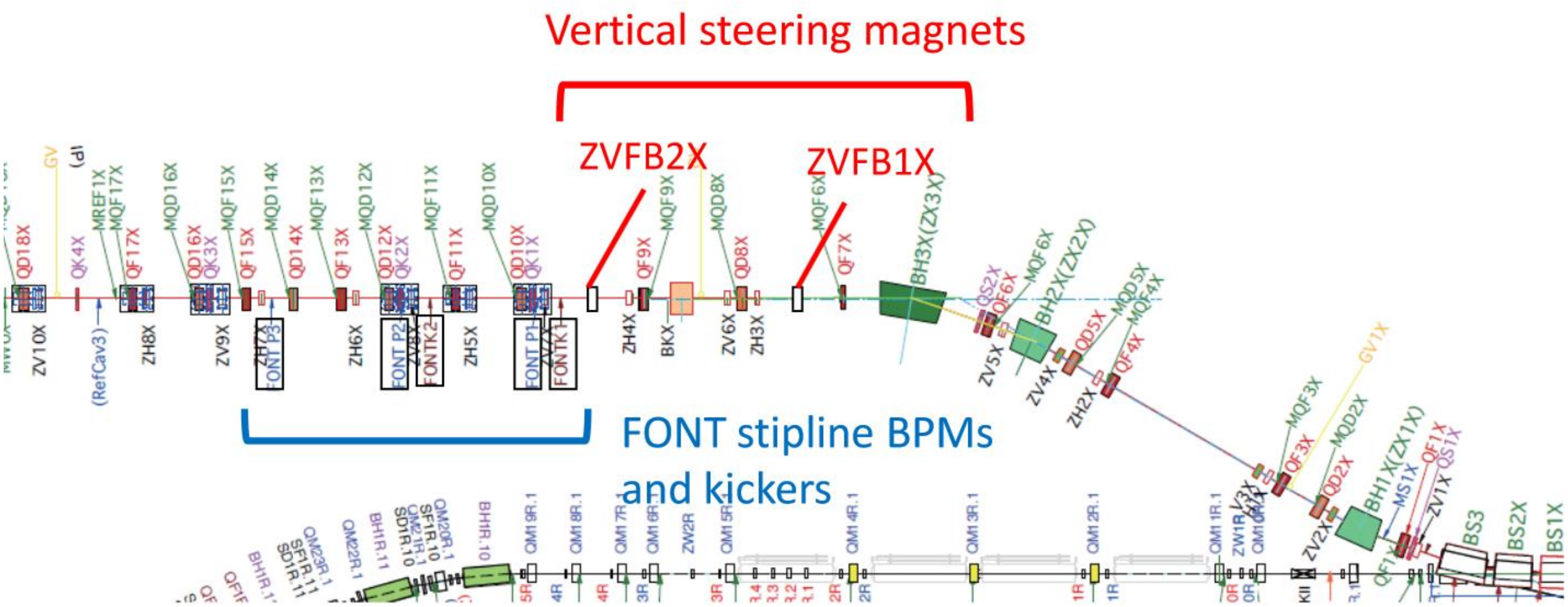
Electronics latency ~ 13ns
Drive power > 50nm
@ CLIC

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

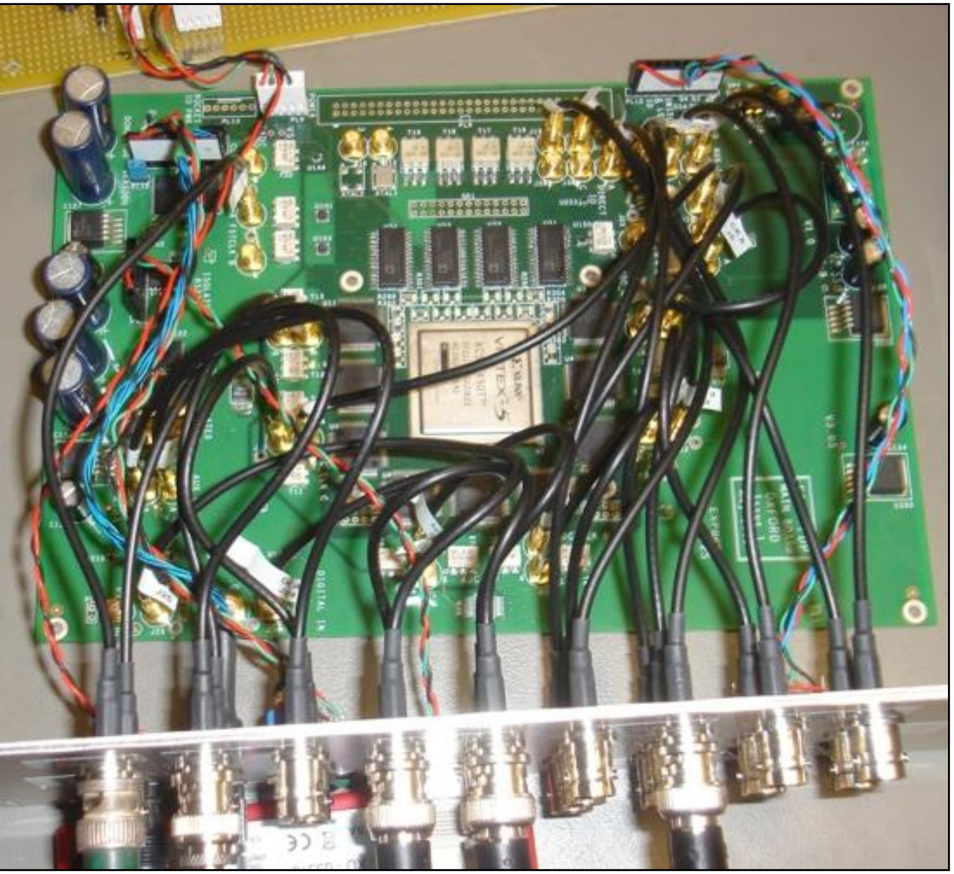
Random jitter source

Random jitter introduced pulse-to-pulse using ZVFB1X & ZVFB2X



from Y. Kano

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)

FONT4 drive amplifier

- FONT4 amplifier, outline design done in JAI/Oxford
- Production design + fabrication by TMD Technologies
- Specifications:

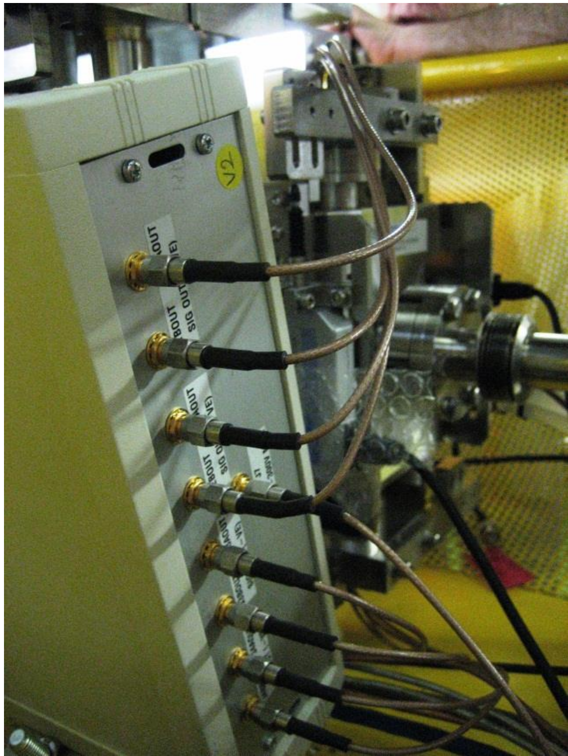
+- 15A (kicker terminated with 50 Ohm)

+- 30A (kicker shorted at far end)

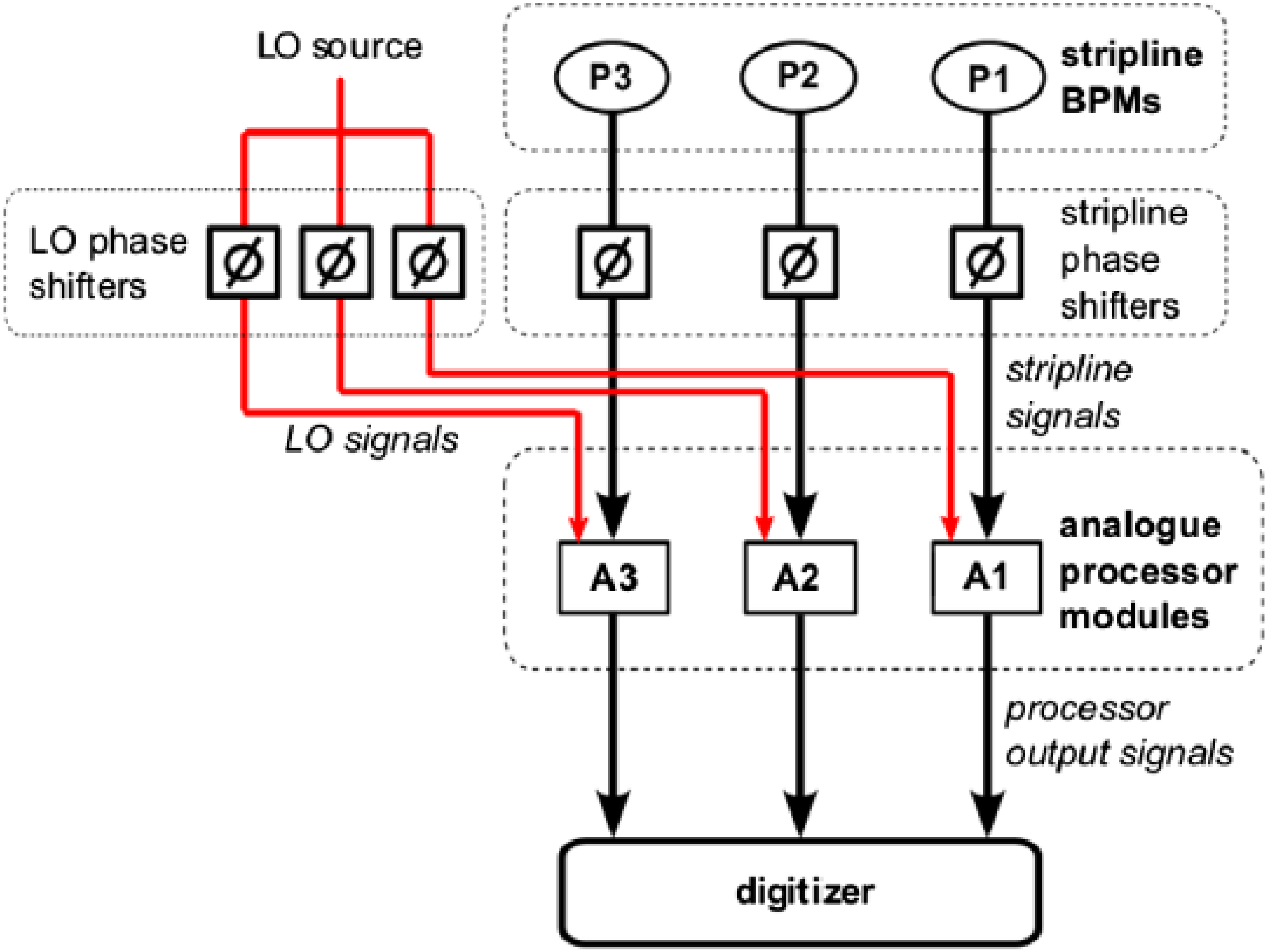
35ns risetime (to 90%)

pulse length 10 us

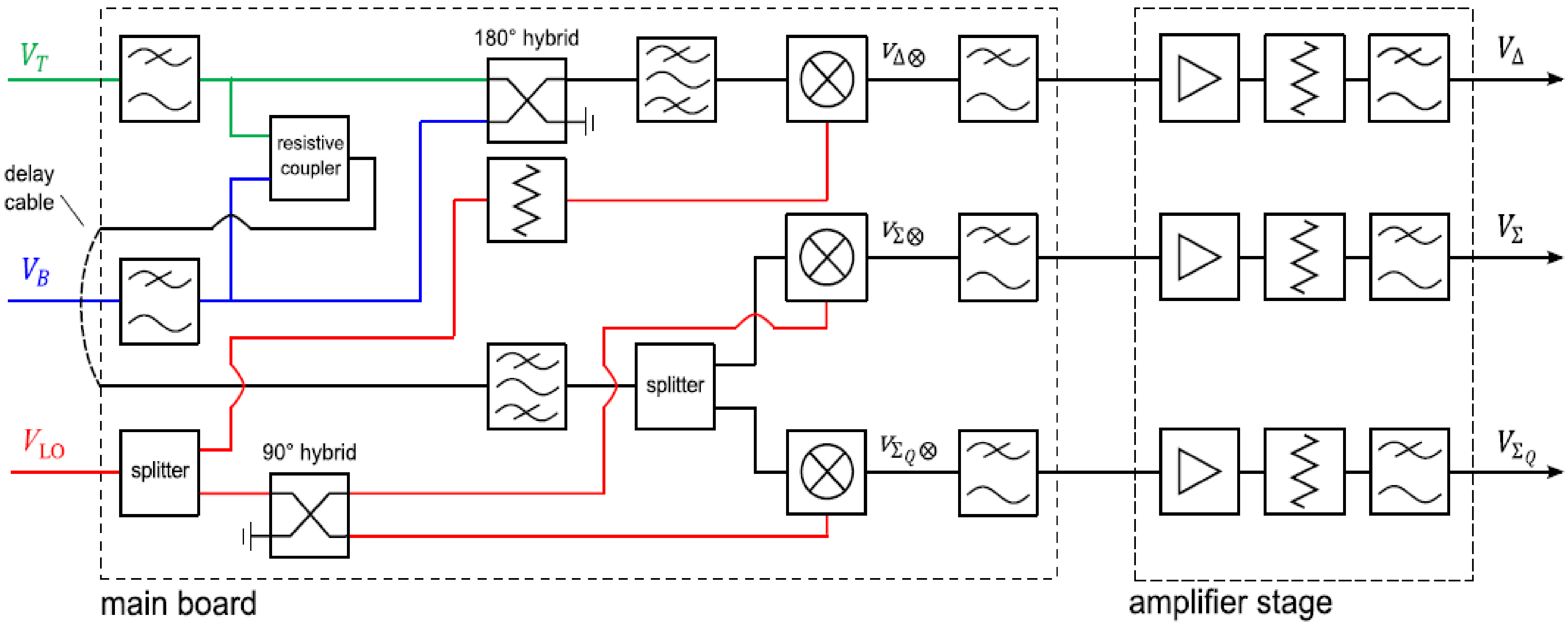
repetition rate 10 Hz



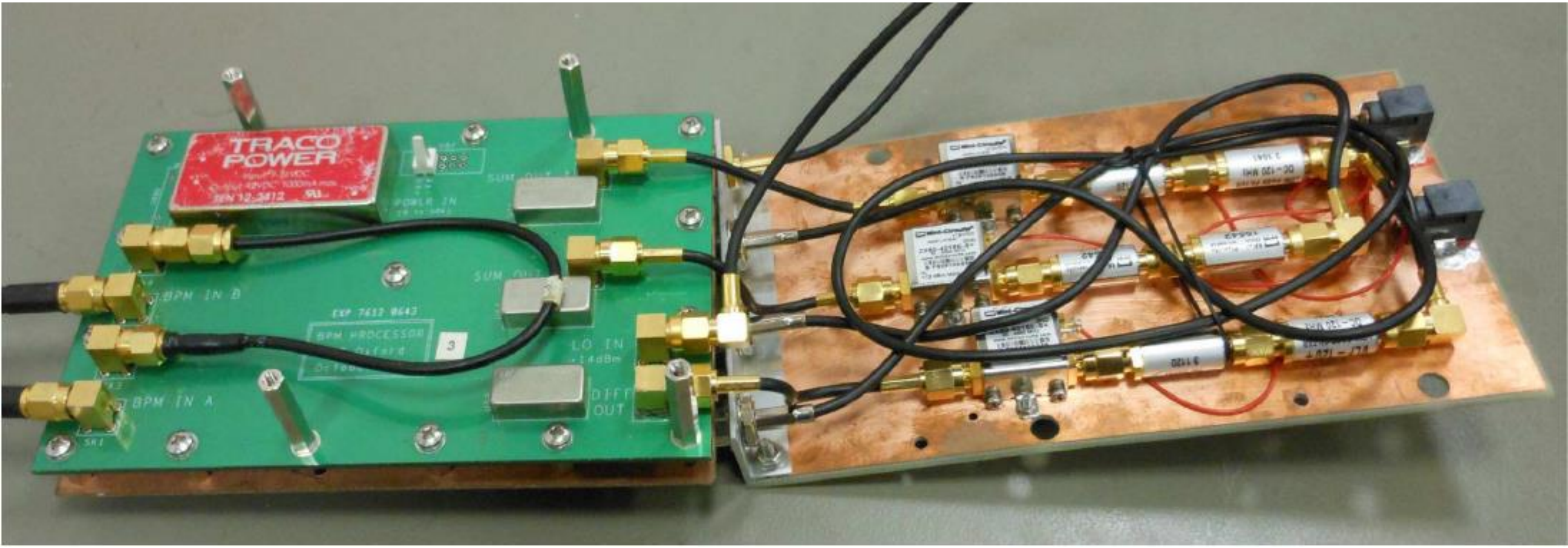
BPM readout


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

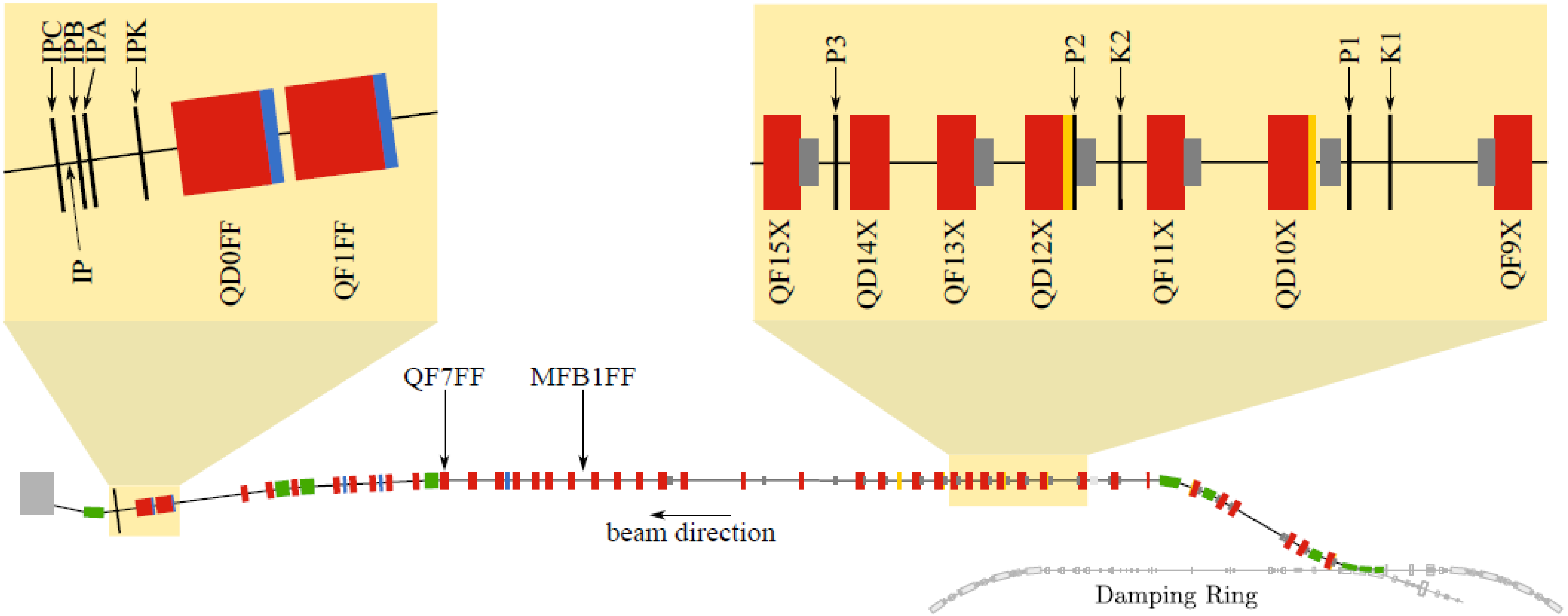
BPM signal processing



BPM signal processor

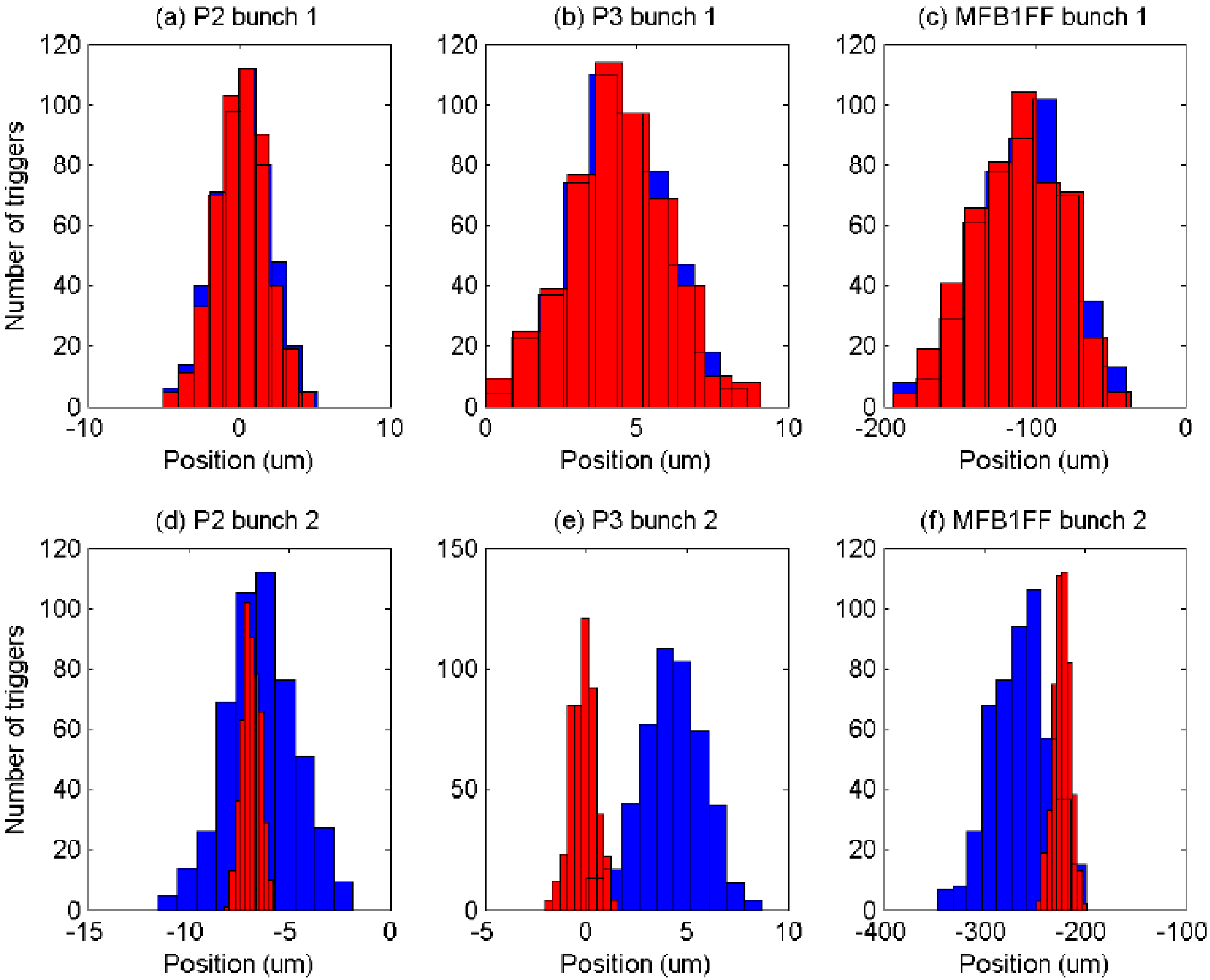


Stabilising beam near IP



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

FONT5 system performance



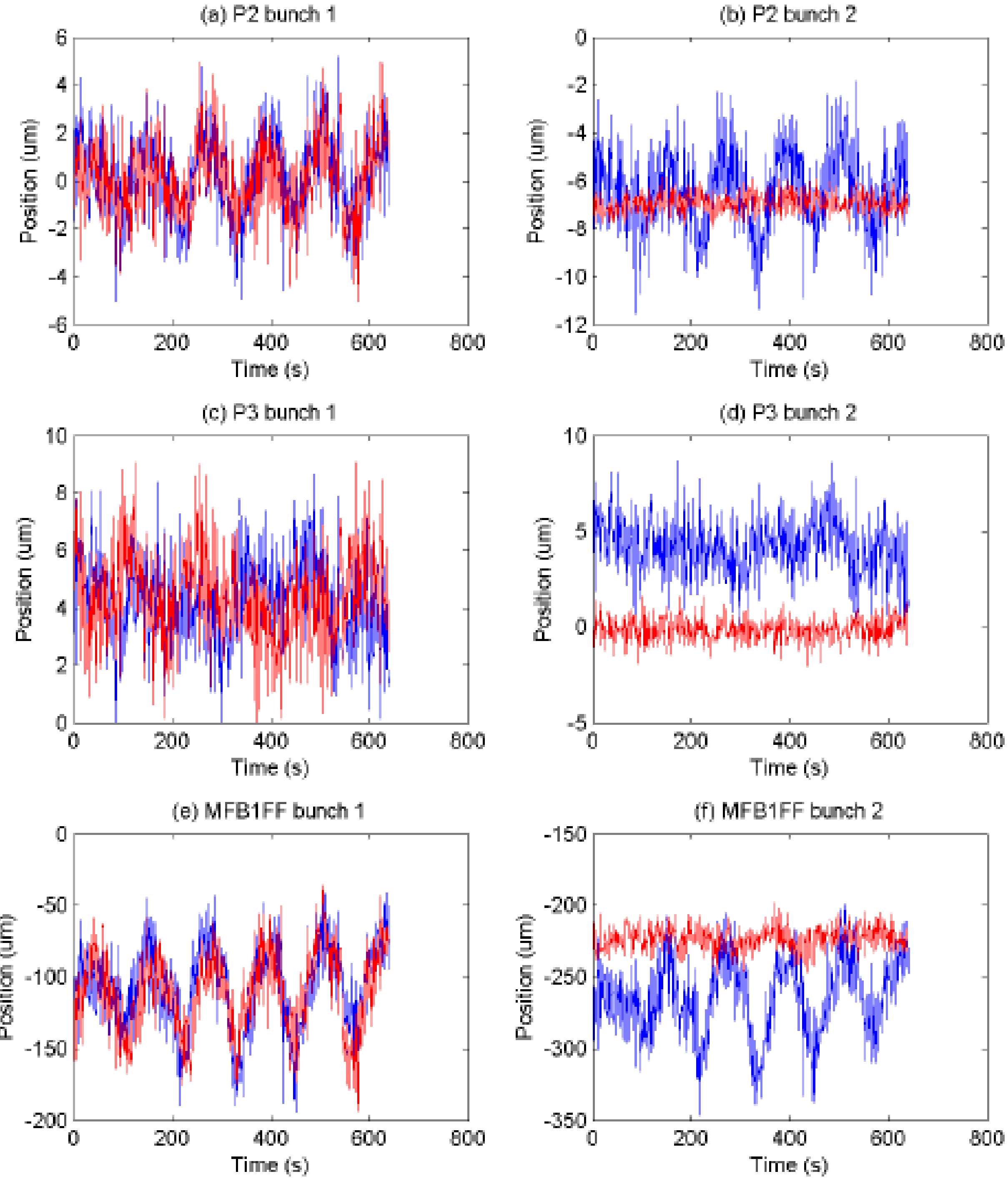
Bunch 1: input to FB

FB off
FB on

Bunch 2: corrected

FB off
FB on

Time sequence



Bunch 2: corrected

FB off

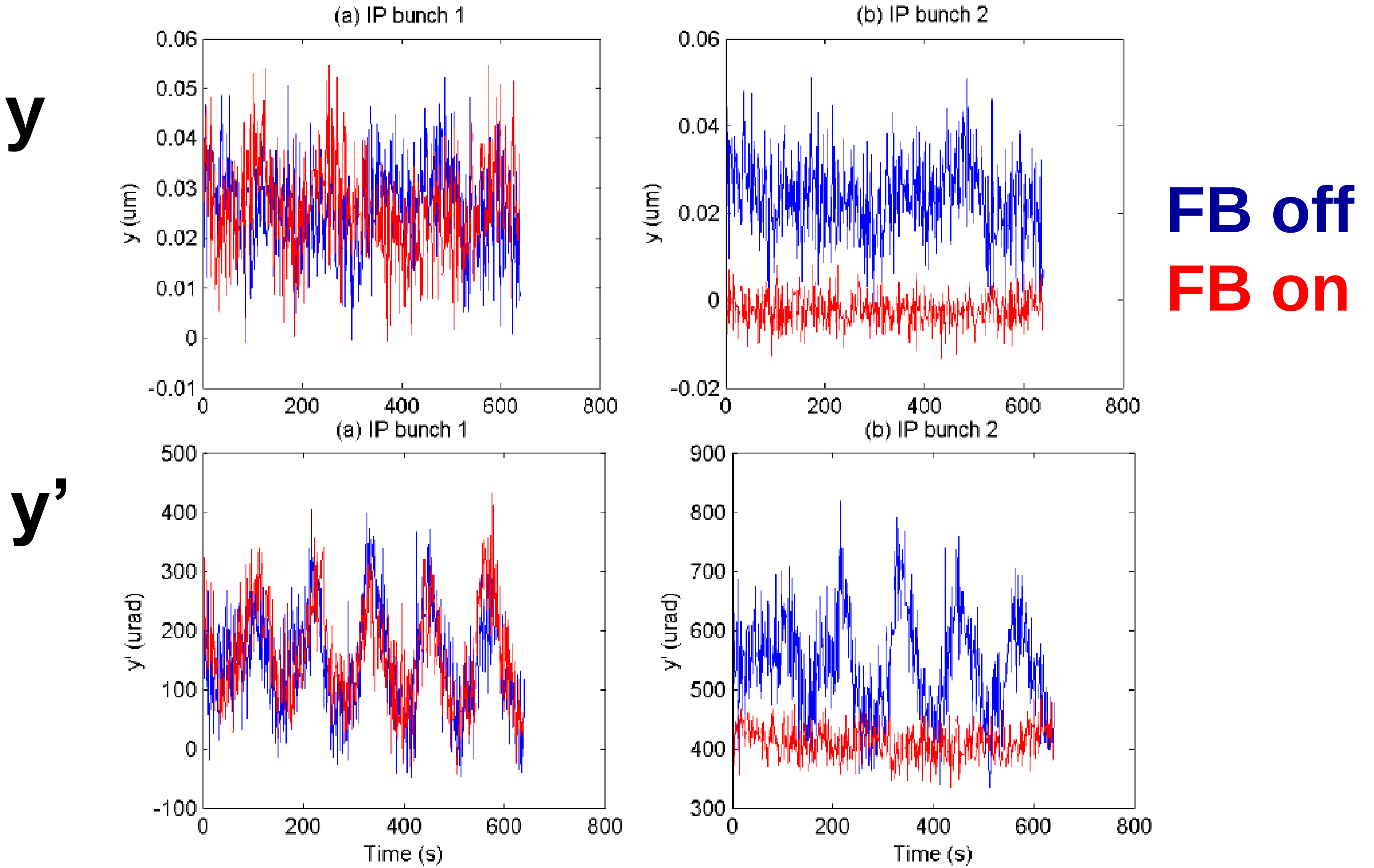
FB on

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

Predicted jitter reduction at IP



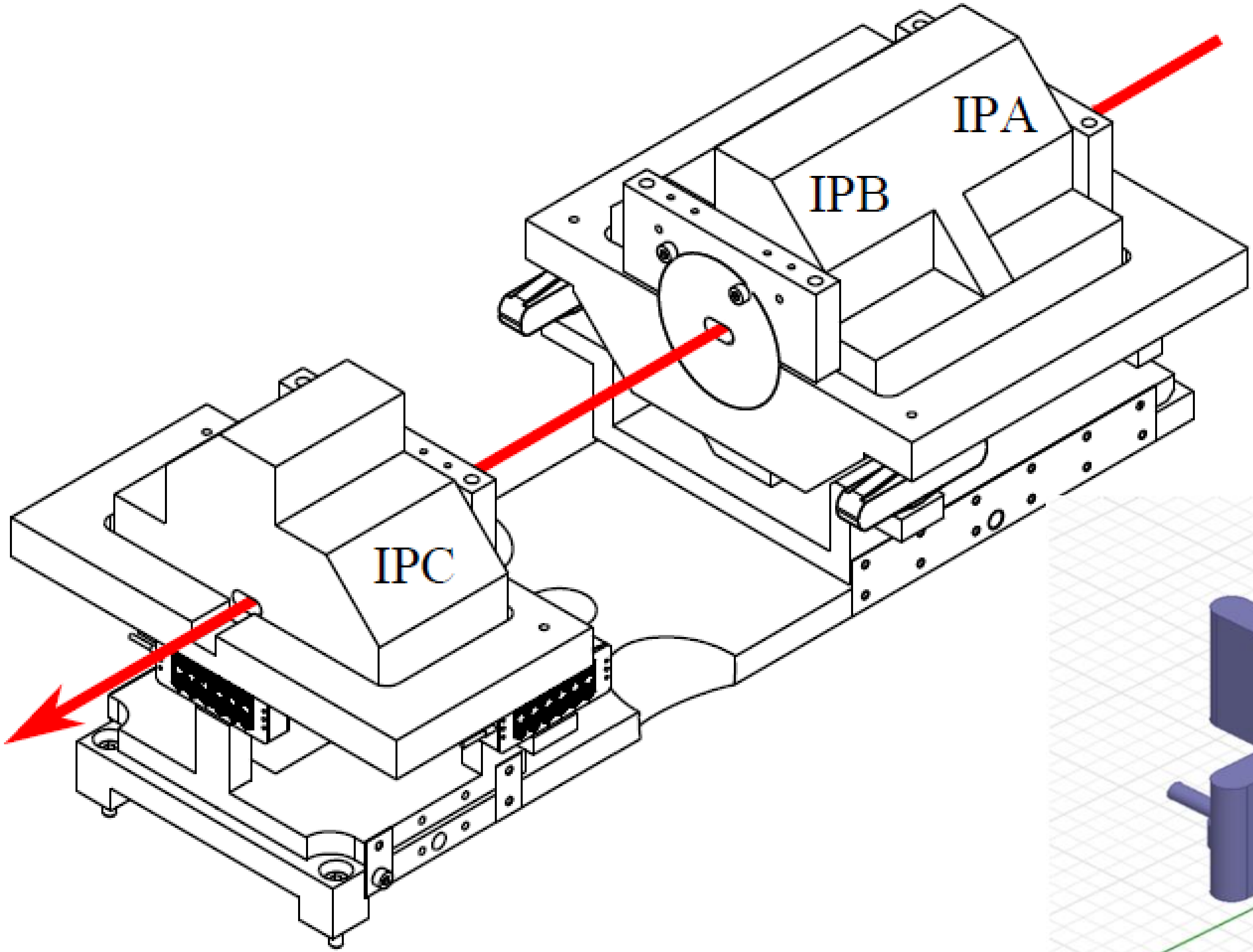
Predicted jitter reduction at IP

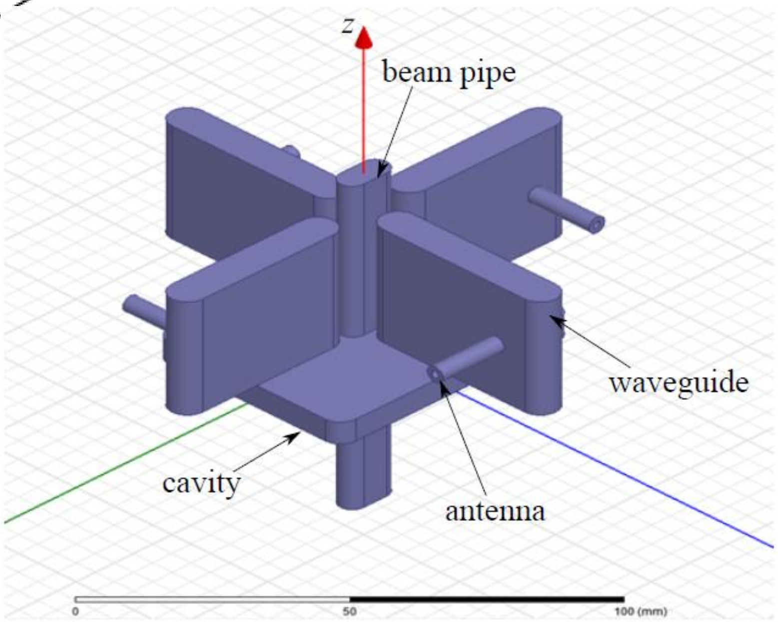
	Position y jitter (nm)		Angle y' jitter (urad)	
Bunch	Feedback off	Feedback on	Feedback off	Feedback on
1	9.5 ± 0.3	10.1 ± 0.3	89 ± 3	87 ± 3
2	9.4 ± 0.3	3.6 ± 0.1	87 ± 3	28 ± 1

Predict position stabilised at few nanometre level…

How to measure it?!

IP cavity BPM system



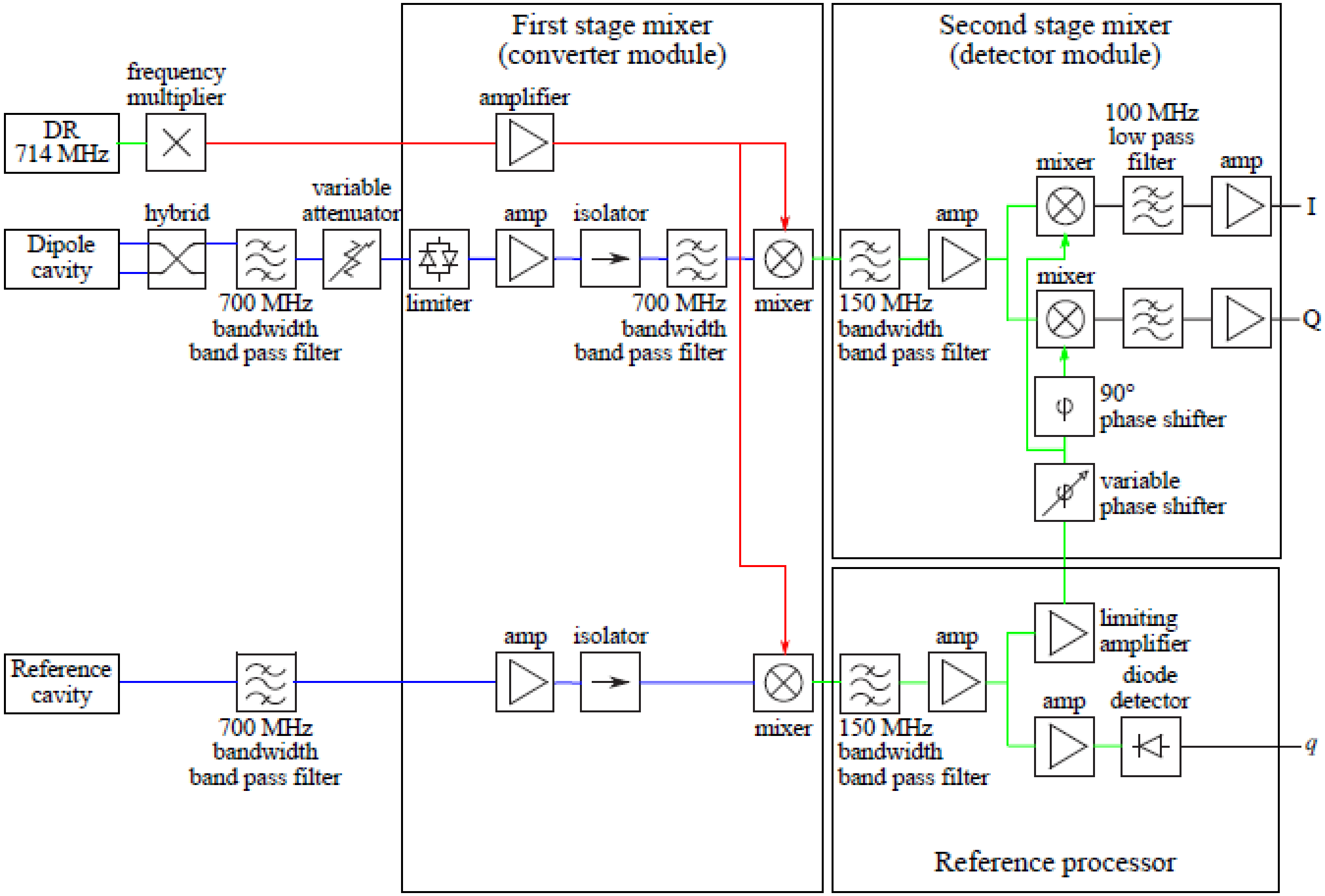


Low-Q cavity BPMs

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



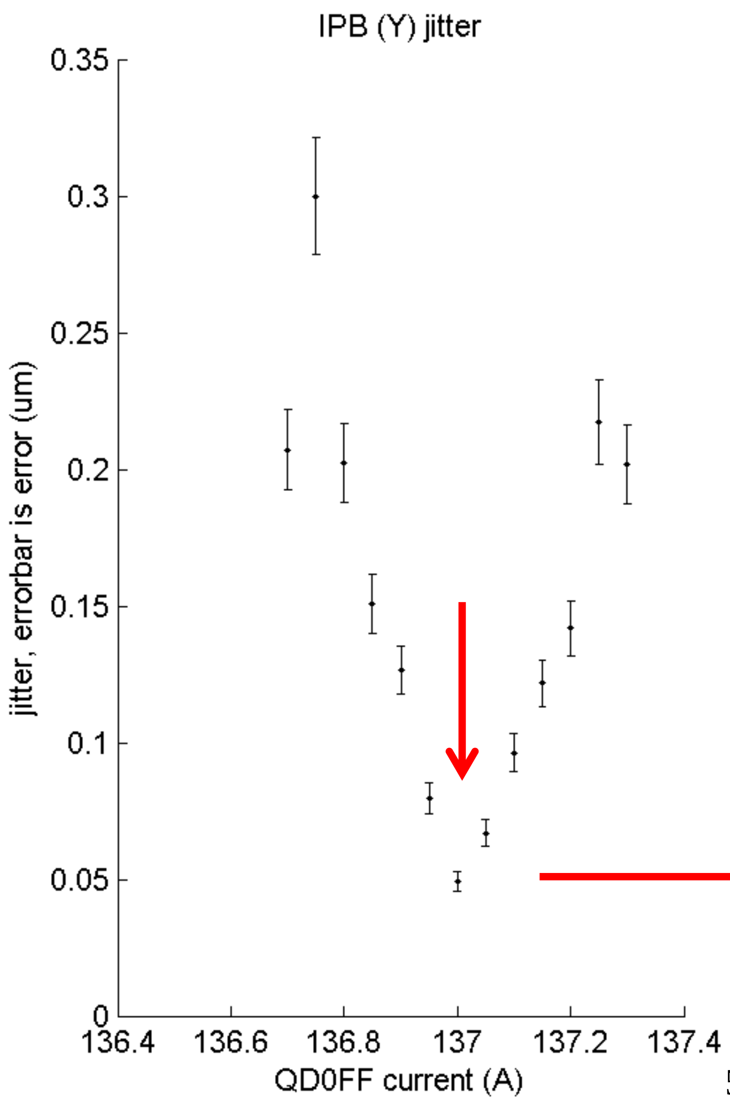
I → I'

Q → Q'

bunch charge

Honda

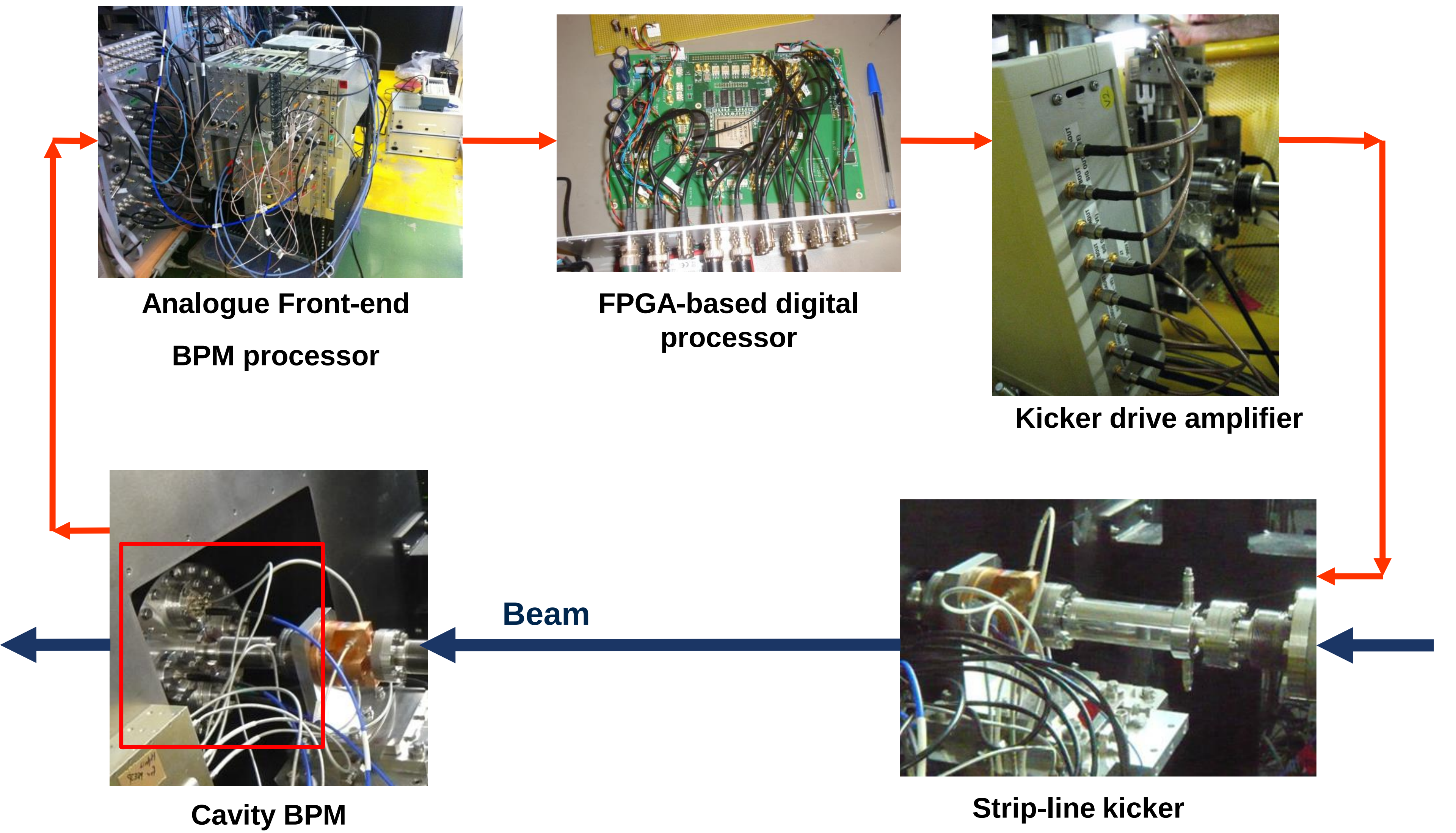
Jitter vs. QD0FF setting (waist scan)



minimum jitter:

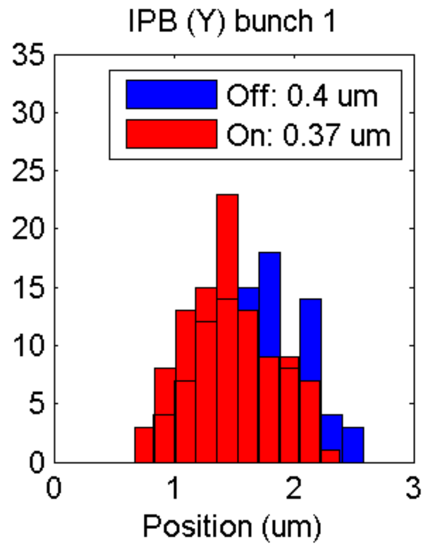
49 nm (integration)

Interaction Point FONT System

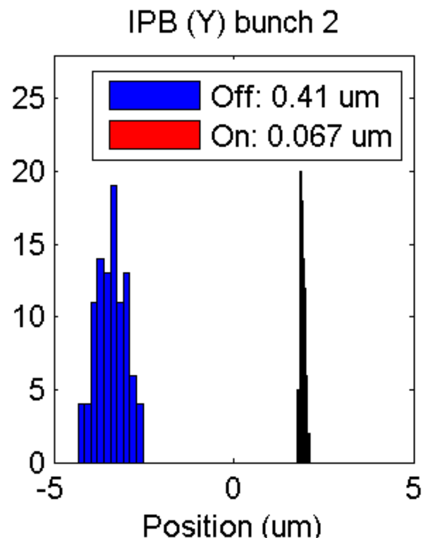


IPFB results

Bunch 1:
not corrected,
jitter ~ 400nm



Bunch 2:
corrected,
jitter ~ 67nm



Corrected jitter 67nm

→ resolution 47nm

IPFB results: time sequence