High Resolution Cavity Beam Position Monitor Systems for the Accelerator Test Facility 2 and Future Linear Collider

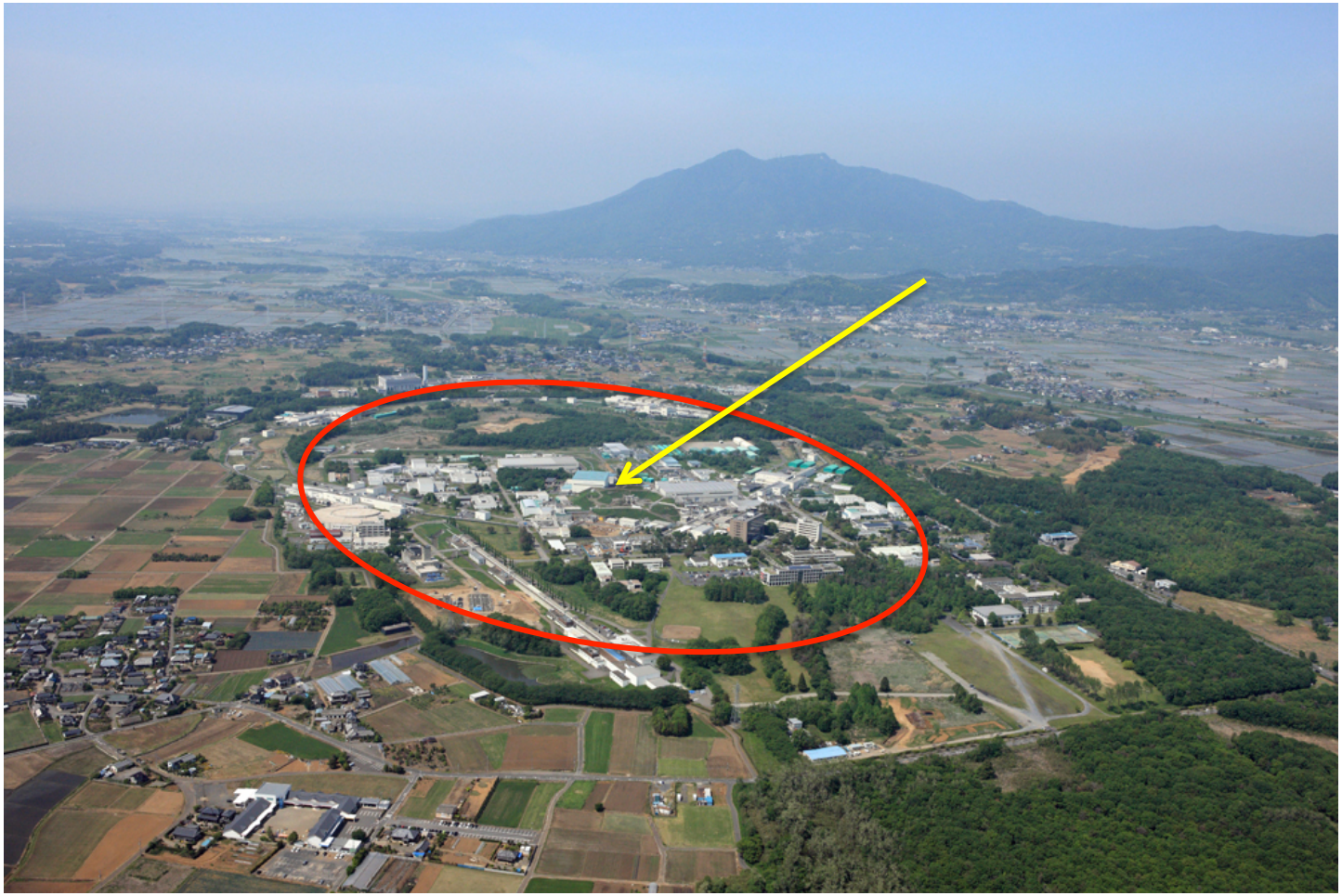
Young-Im Kim

Outline

- Accelerator Test Facility 2, KEK in Japan
- Cavity Beam Position Monitor System (C-, S- band, IPBPM)
  - Principle
  - Electronics
  - Signal processing
  - Calibration
  - Performance results
- IP Feedback at ATF2
- Tracking simulation
- Summary

KEK

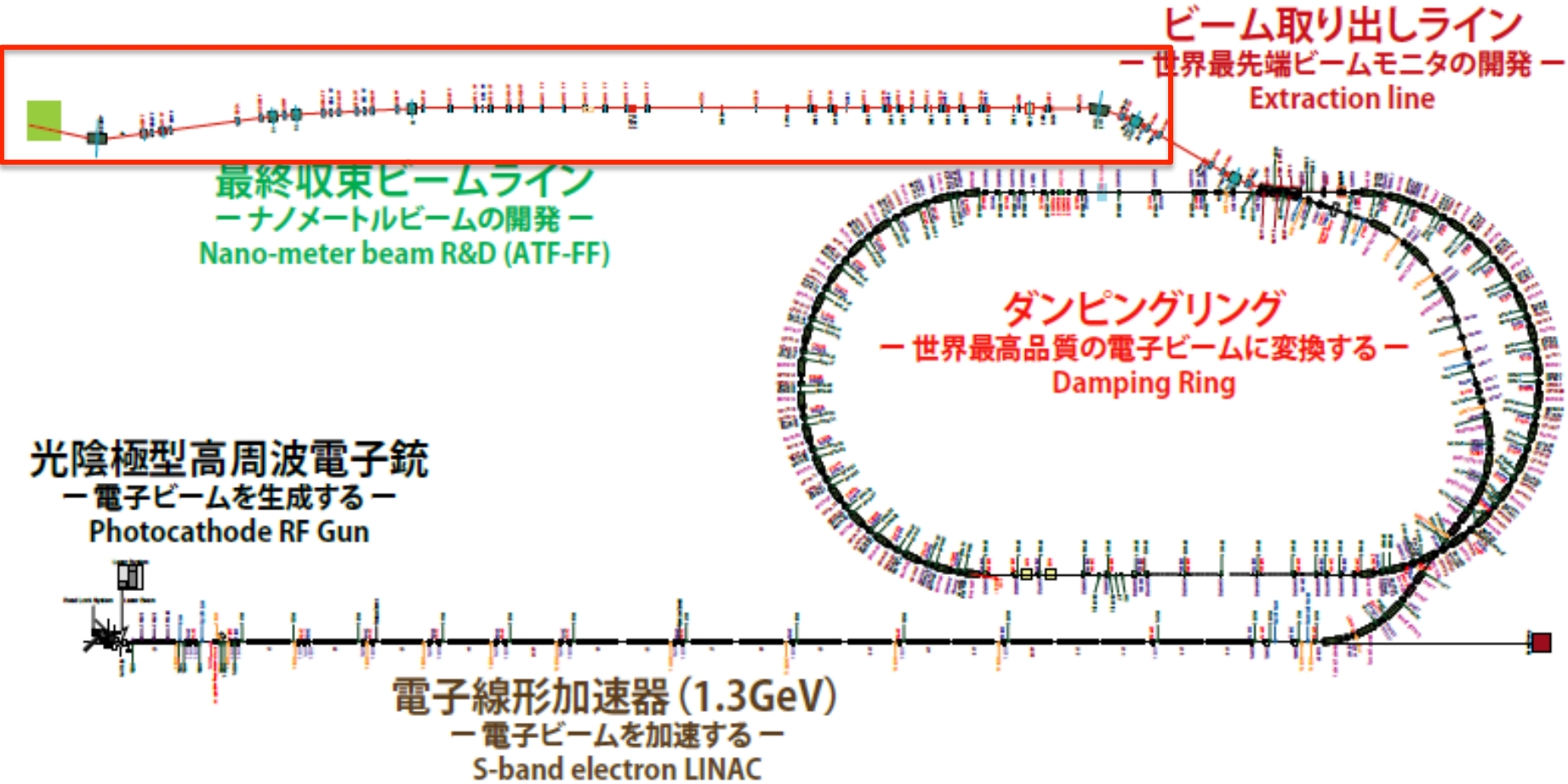
- High Energy Accelerator Research Organization



Accelerator Test Facility (KEK)

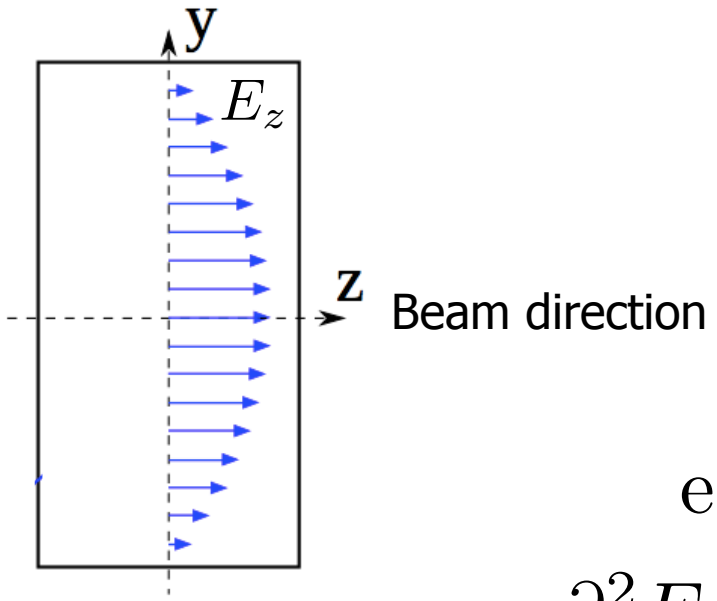
- Located at KEK in Tsukuba, Japan
- 1.3 GeV electron damping ring (prototype for ILC)
  - Designed to achieve super-low beam emittance
  - Successfully produced beams with low emittance, 3-4 pm in both single and multi-bunch modes
- ATF2 upgrade in 2008 replaced the extraction line
  - Goal 1: 37 nm vertical beam size at the final focus
  - Goal 2: Stabilize beam at final focus with 2 nm precision
- Operation rate 1.56 Hz (recently doubled to 3.12 Hz)
- Multi-bunch trains
  - Bunch spacing 150 – 300 ns

ATF/ATF2


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

Basic principle

Rectangular cavity



$$\text{eigenmode with } \mathbf{E} = (0, 0, E_z)$$

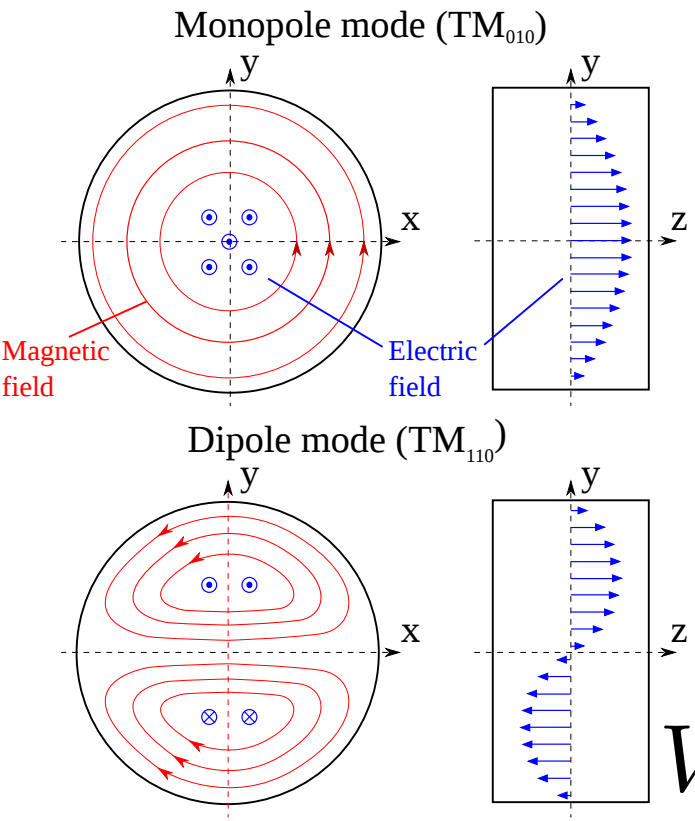
$$\text{wave equation : } \frac{\partial^2 E_z}{x^2} + \frac{\partial^2 E_z}{y^2} + \frac{\partial^2 E_z}{z^2} = \frac{1}{c^2}\frac{\partial^2 E_z}{t^2}$$

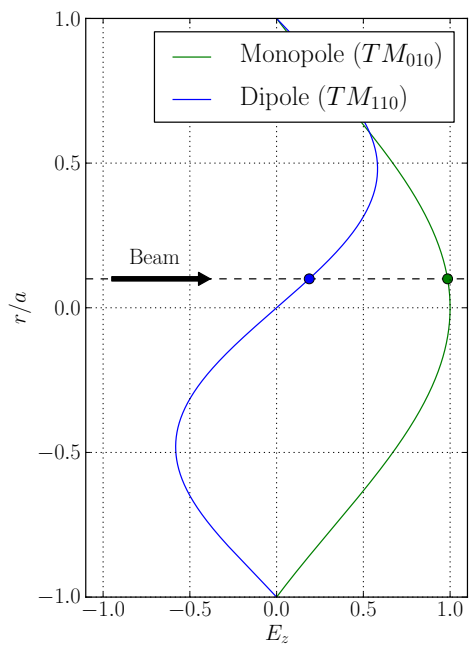
$$\text{boundary conditions } E_z = 0 \text{ at } x \pm a, y \pm a$$

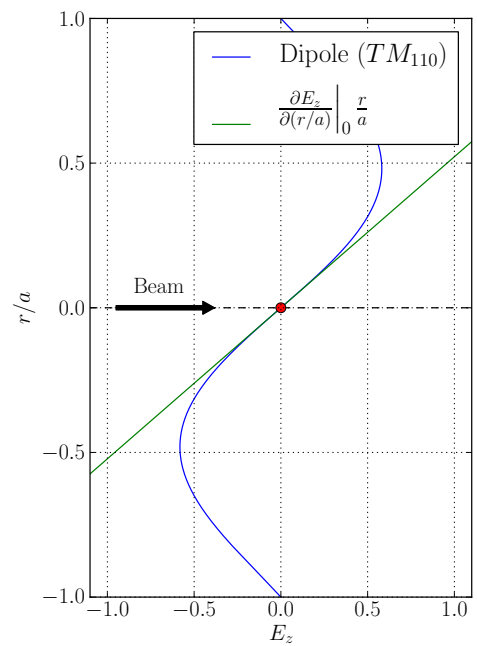
Basic principle

Simplest practical model of accelerating cavity: hollow cylinder

Field pattern: for particle acceleration we need longitudinal electric field on the axis
⇒ choose TM (transverse magnetic) eigenmode of cavity



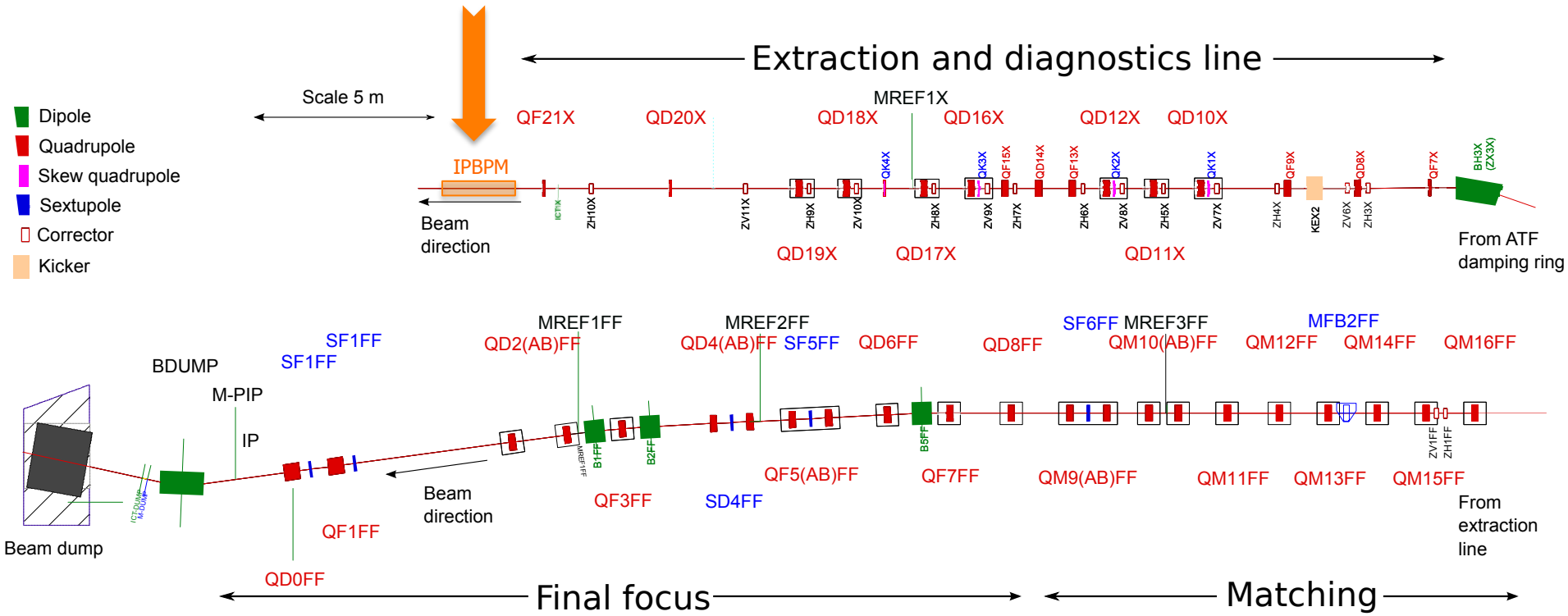




$$V_{\text{monopole}} \propto q \quad V_{\text{dipole}} \propto q \times d$$

Accelerator Test Facility 2

- ATF2, KEK, Japan



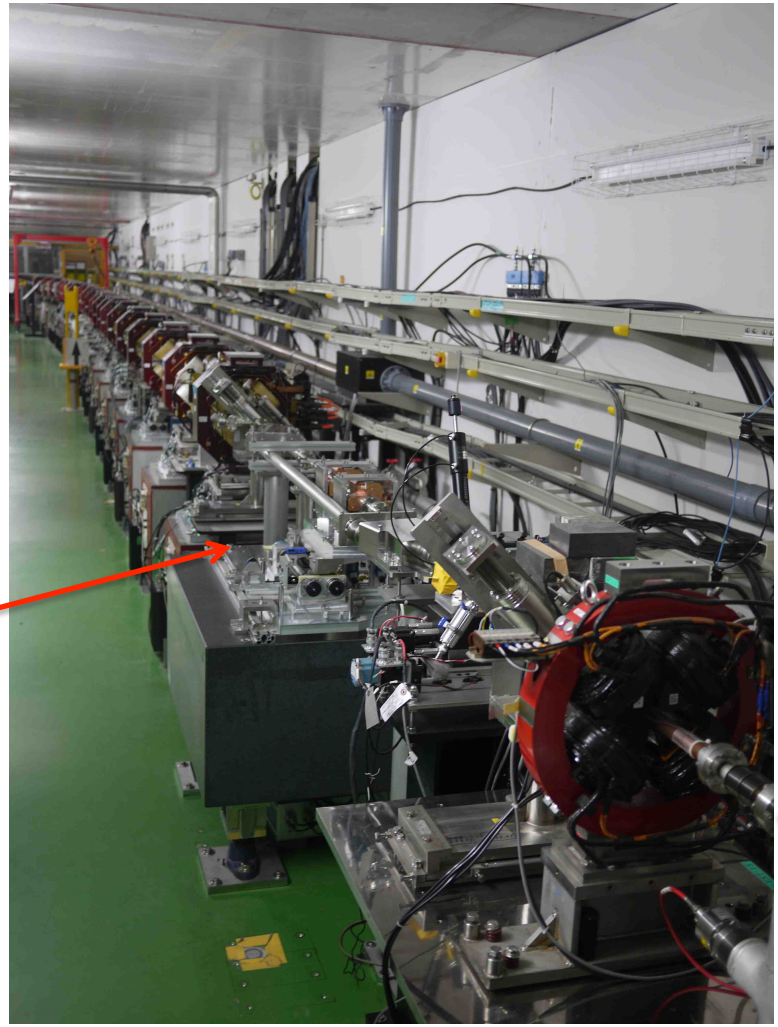
- 38 position sensitive dipole cavities (34 C-band, 4 S-band)
- Specialized IPBPM

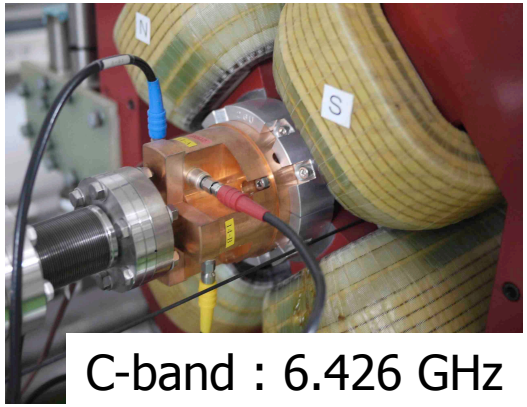
Accelerator Test Facility 2

Interaction point

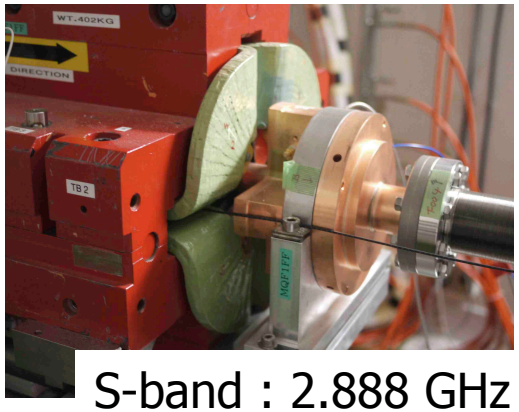
IPBPM test location

2011 Nov. ~ Dec.





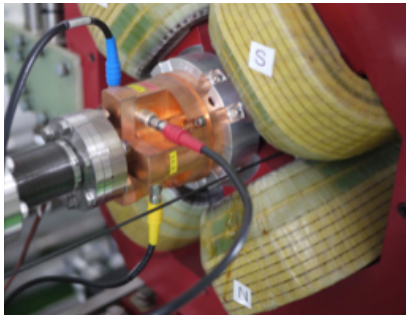
C-band : 6.426 GHz

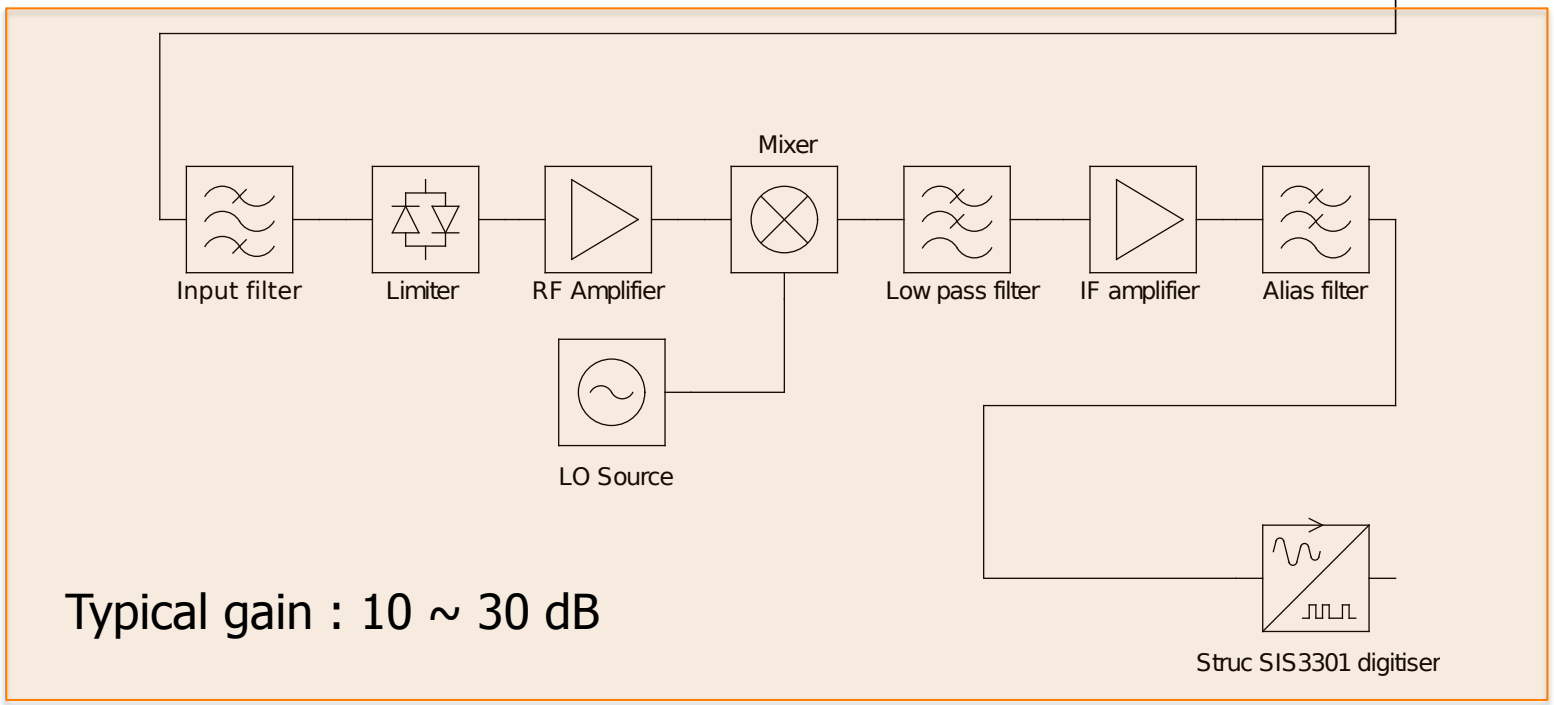


S-band : 2.888 GHz

From damping ring

Radio frequency signal processing

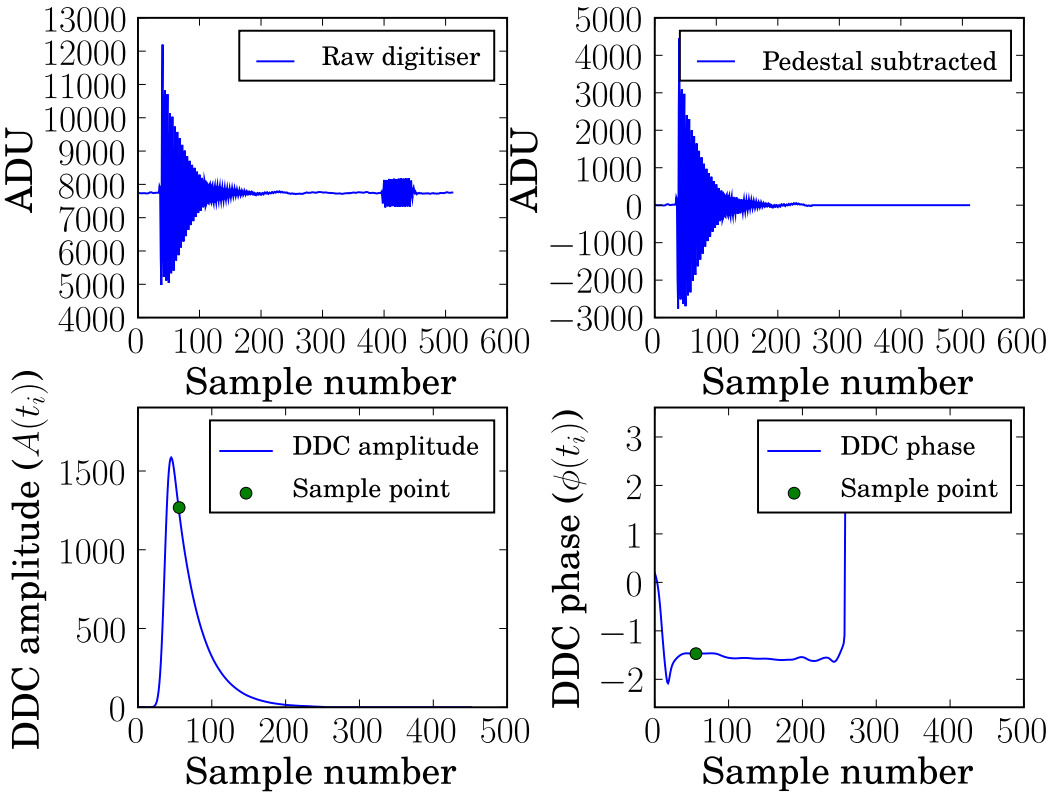




Typical gain : 10 ~ 30 dB

Digital signal processing

Digital down conversion (DDC)



1) Mix and filter

$$y_{DDC} = Filt\left[V_{cavity} \times V_{LO}\right]$$

2) Calculate amplitude and phase

$$A(t_i) = \sqrt{y_{DDC}(t_i) \cdot y^*_{DDC}(t_i)}$$

$$\phi(t_i) = \arctan\left[\frac{\mathrm{Im}[y_{DDC}(t_i)]}{\mathrm{Re}[y_{DDC}(t_i)]}\right]$$

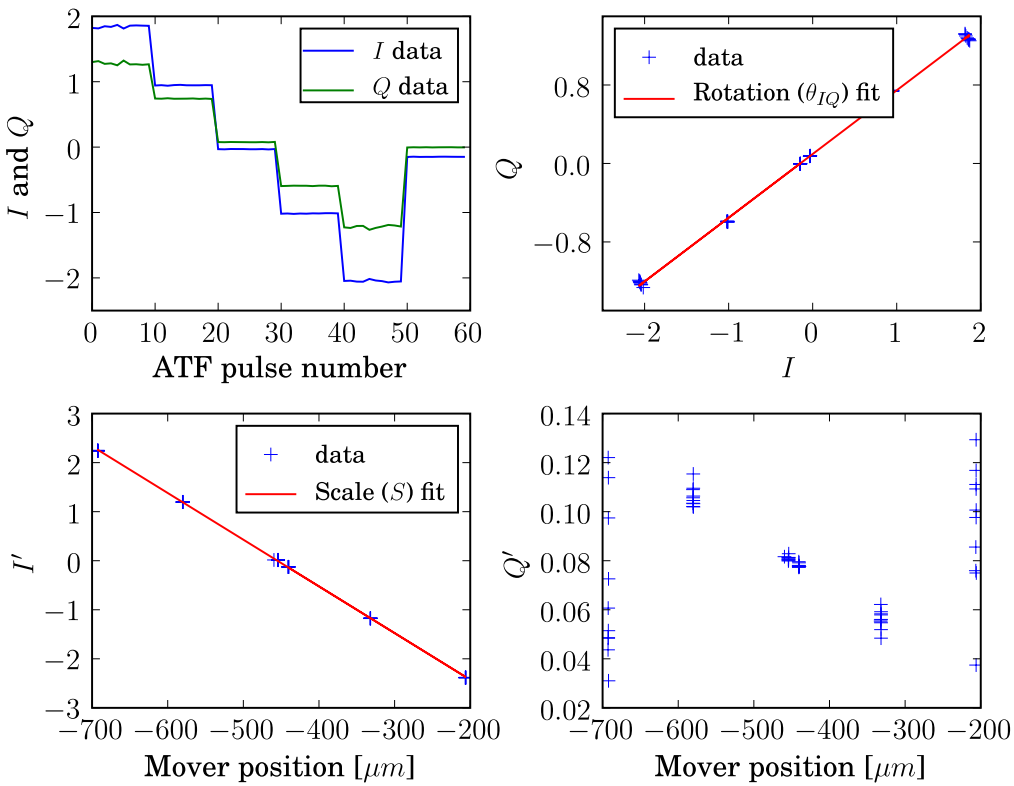
3) Calculate I and Q compared with reference cavity

$$I = \frac{A_d}{A_r}\cos(\phi_d - \phi_r)$$

$$Q = \frac{A_d}{A_r}\sin(\phi_d - \phi_r)$$

Calibration

Mover calibration



1) Determine phasor rotation to position

$$\theta_{IQ} = \tan^{-1}\left(\frac{dQ}{dI}\right)$$

2) Rotate phasor so I′ is proportional to position

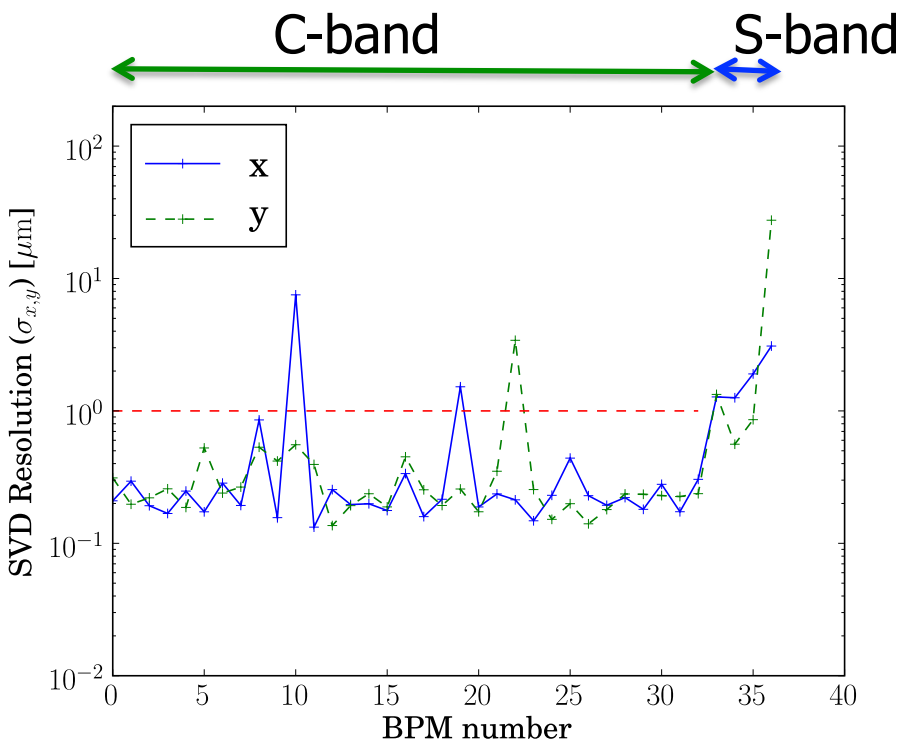
$$I' = I\cos(\theta_{IQ}) + Q\sin(\theta_{IQ})$$
$$Q' = -I\sin(\theta_{IQ}) + Q\cos(\theta_{IQ})$$

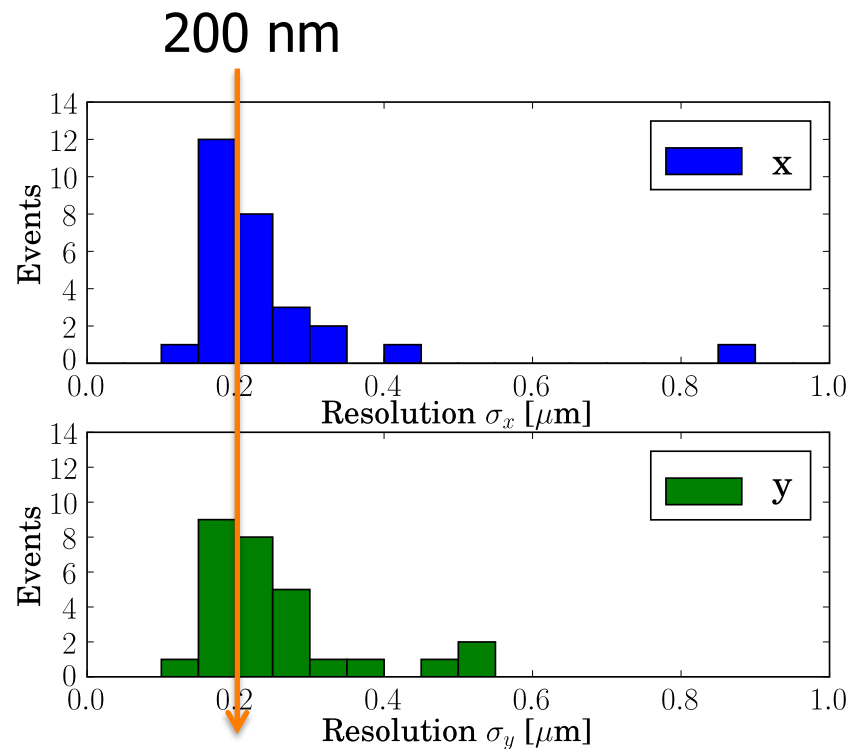
3) Determine scale between I′ and mover position

$$y = \boxed{\frac{dY_{mover}}{dI'}} \cdot I'$$

$$\frac{1}{S}$$

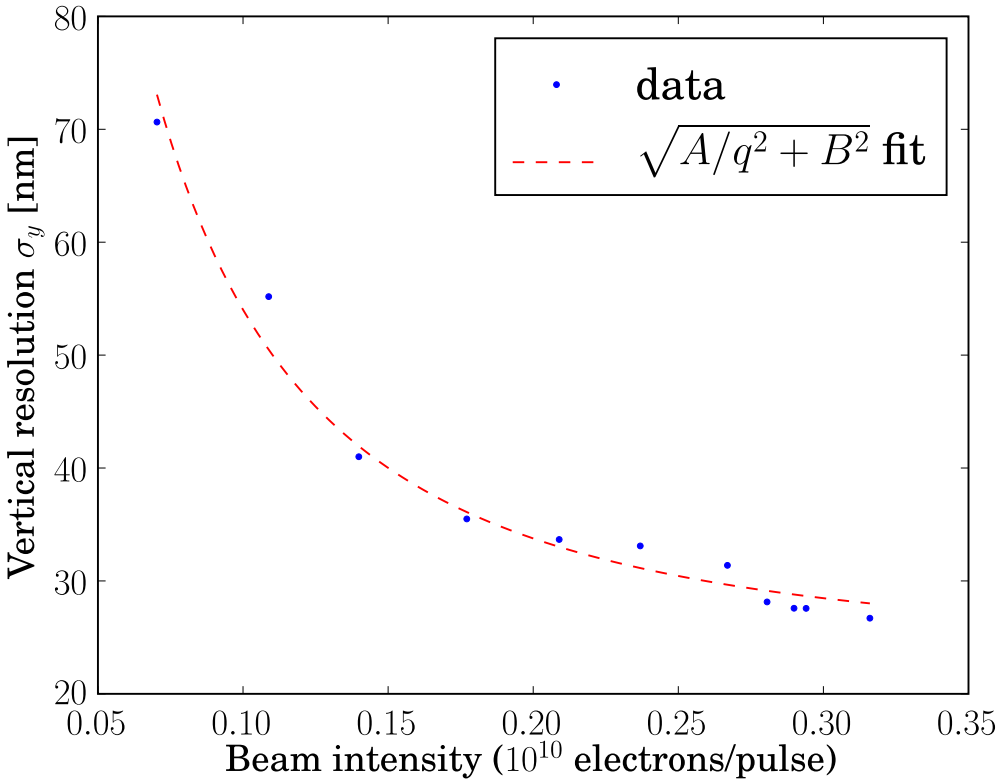
System performance

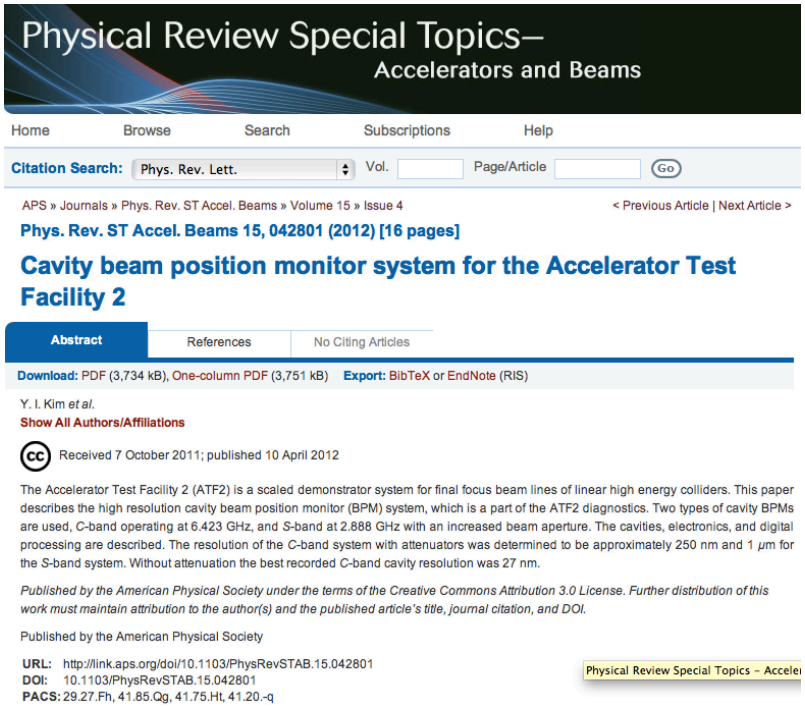




Best resolution of C-band BPM at ATF2

Final result, published in Phys. Rev. Special Topics – Accelerators and Beams 15, 042801 (2012)
Cavity beam position monitor system for the Accelerator Test Facility 2 – Y. I. Kim *et al.*





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Cavity beam position monitor system for the Accelerator Test Facility 2

Abstract References No Citing Articles

Download: PDF (3,734 kB), One-column PDF (3,751 kB) Export: BibTeX or EndNote (RIS)

Y. I. Kim *et al.*
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The Accelerator Test Facility 2 (ATF2) is a scaled demonstrator system for final focus beam lines of linear high energy colliders. This paper describes the high resolution cavity beam position monitor (BPM) system, which is a part of the ATF2 diagnostics. Two types of cavity BPMs are used, *C*-band operating at 6.423 GHz, and *S*-band at 2.888 GHz with an increased beam aperture. The cavities, electronics, and digital processing are described. The resolution of the *C*-band system with attenuators was determined to be approximately 250 nm and 1 μm for the *S*-band system. Without attenuation the best recorded *C*-band cavity resolution was 27 nm.

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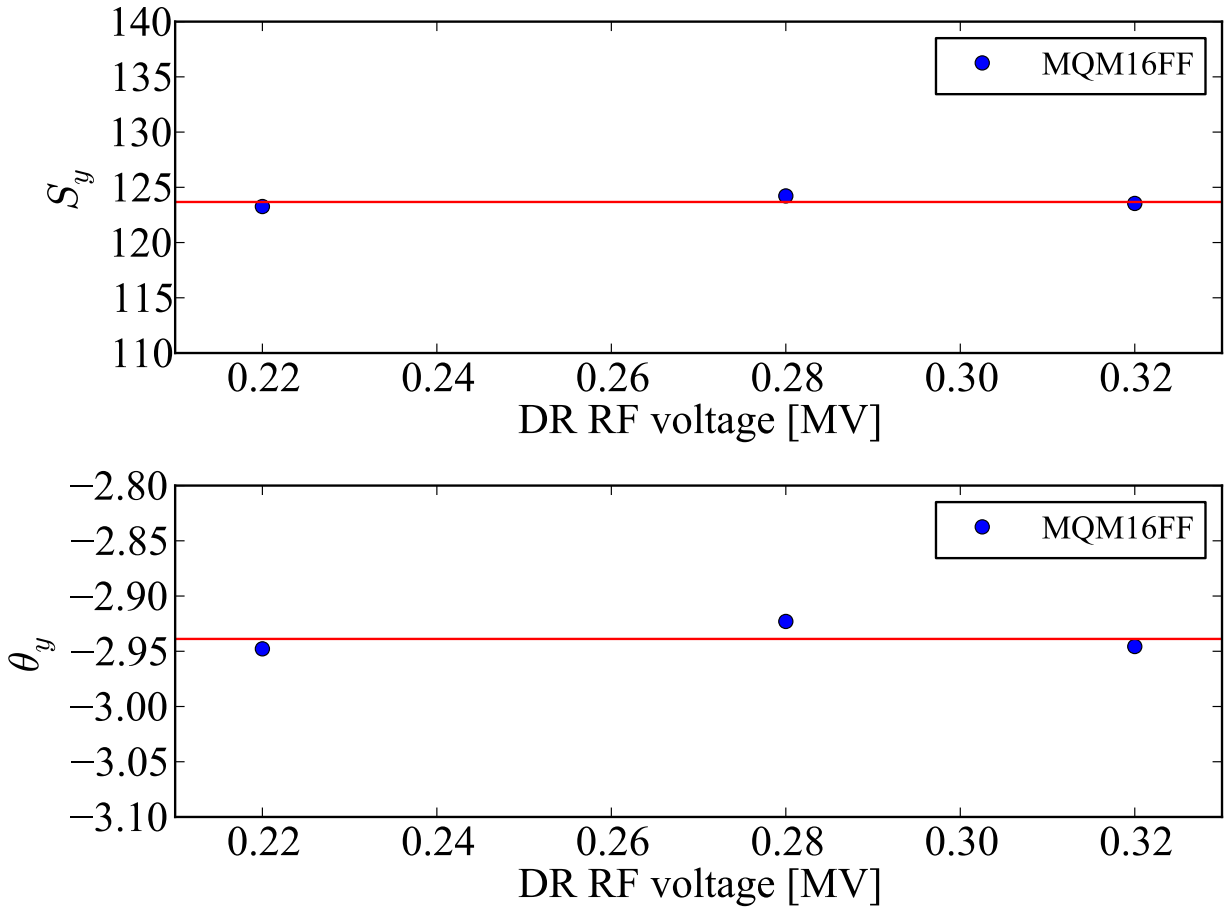
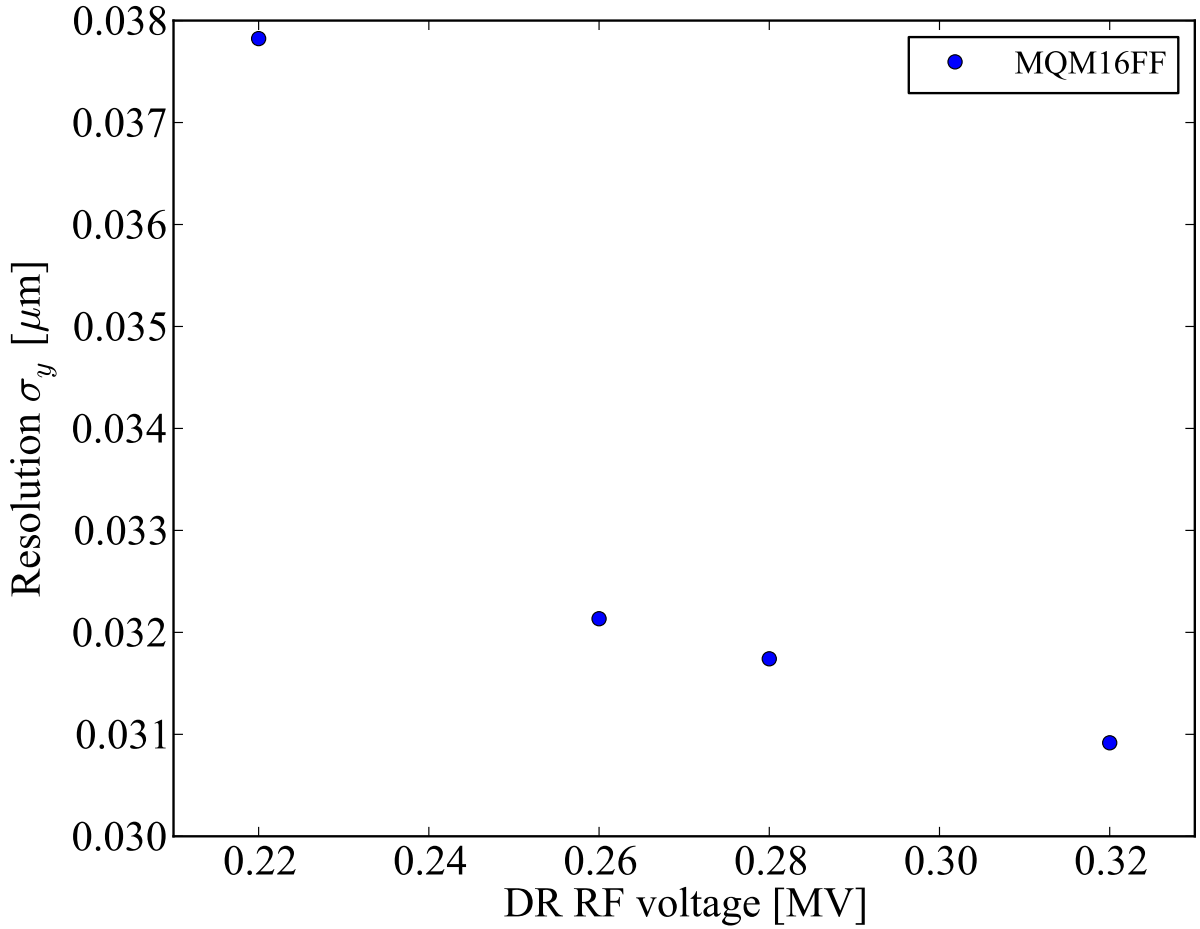
Calibration scale factor



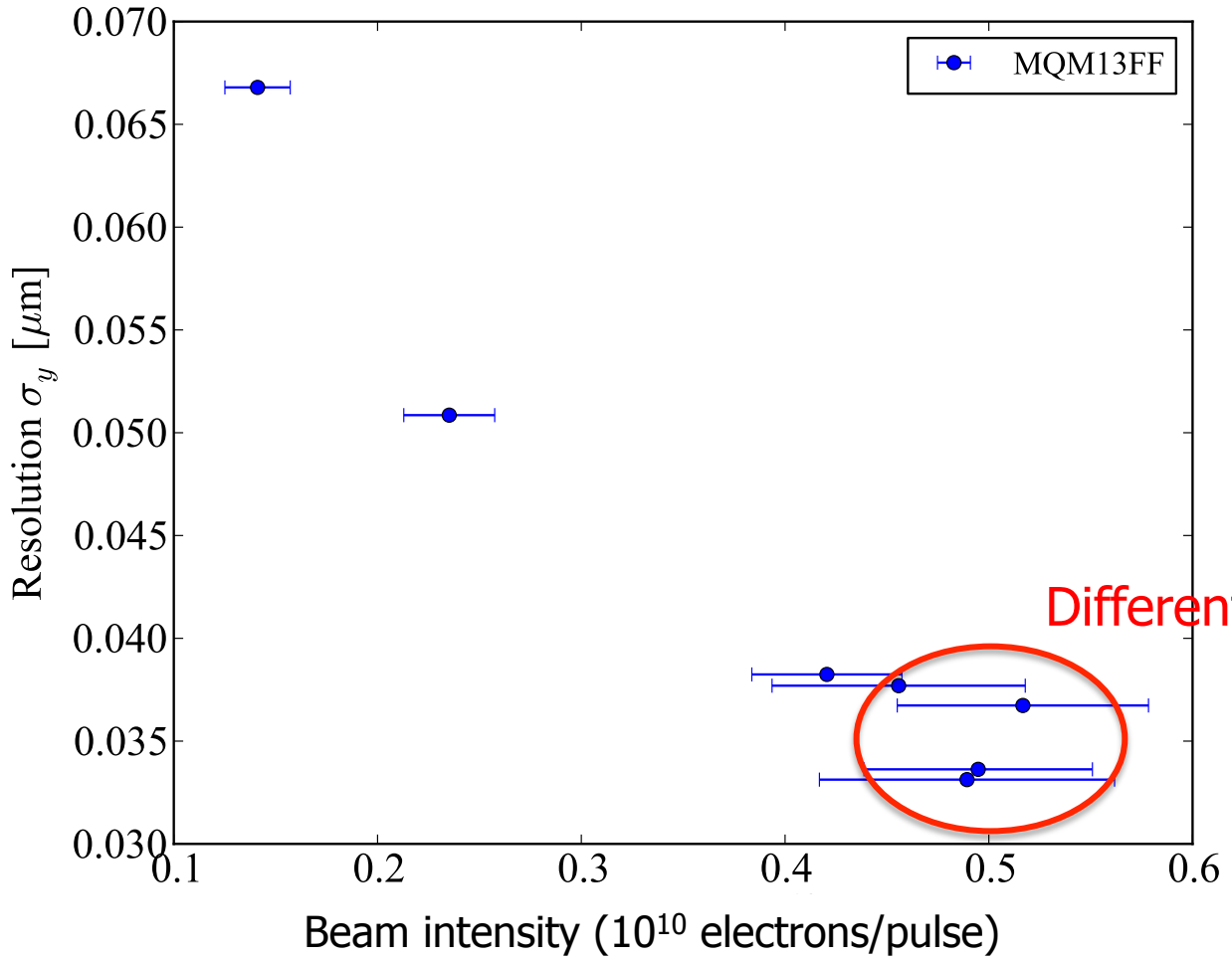
Resolution vs. Bunch length

Cavity BPM without 20 dB attenuator



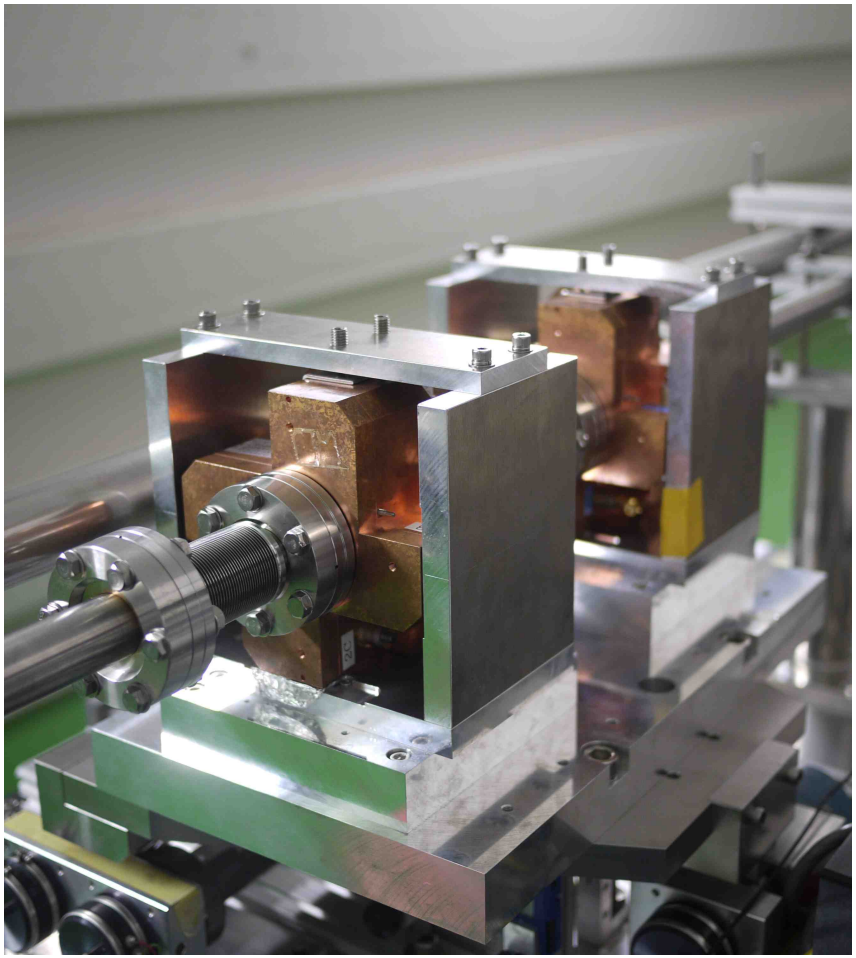
Resolution

Cavity BPM without 20 dB attenuator



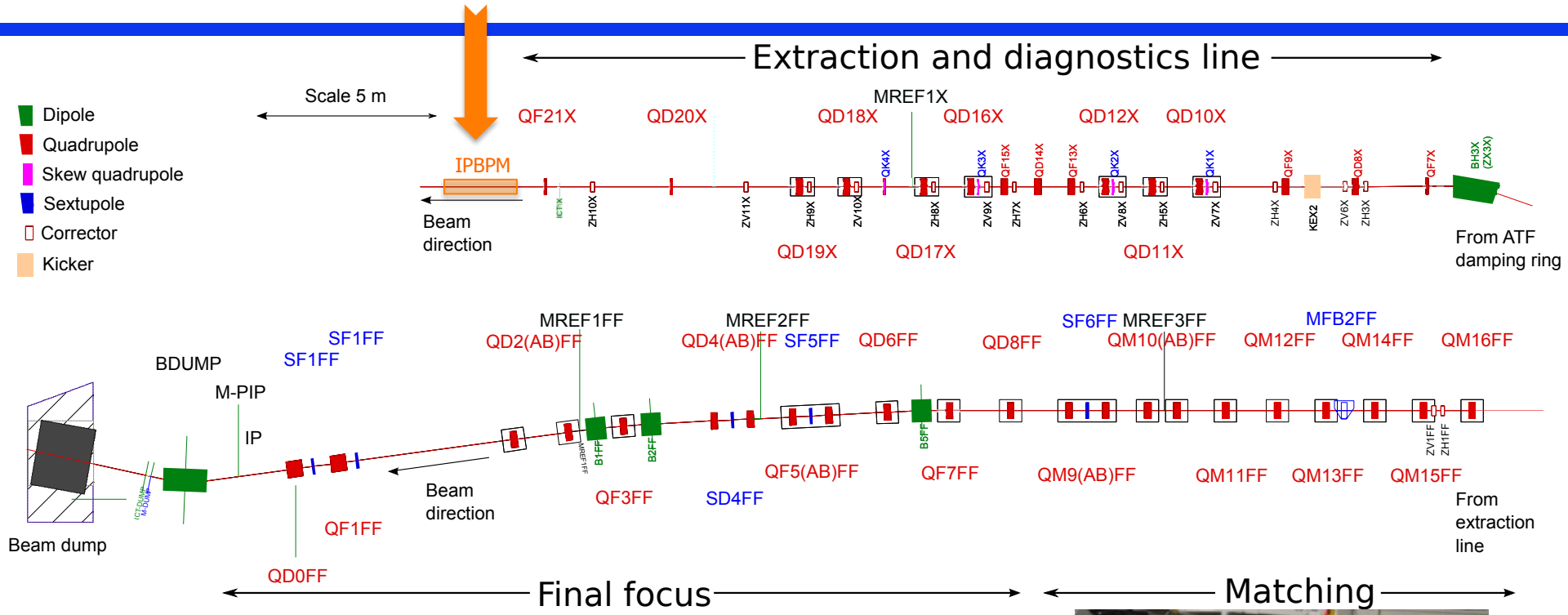
Different bunch length

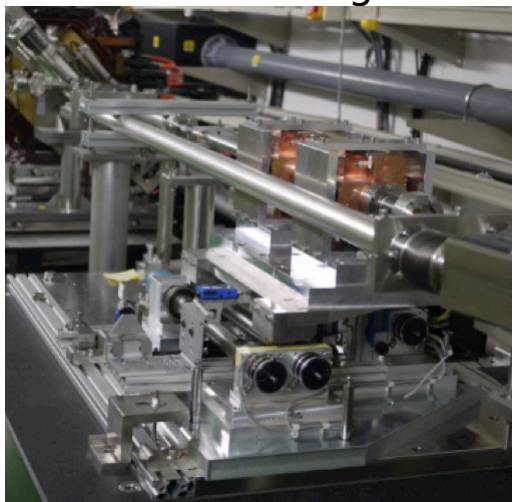
Interaction point BPM (IPBPM)



- Rectangular cavity shape
  - X (5.712 GHz) / Y (6.426 GHz)
- Expected to be large angular jitters @ the IP
  - Low angle sensitivity
    - Short cavity (6 mm, z direction)

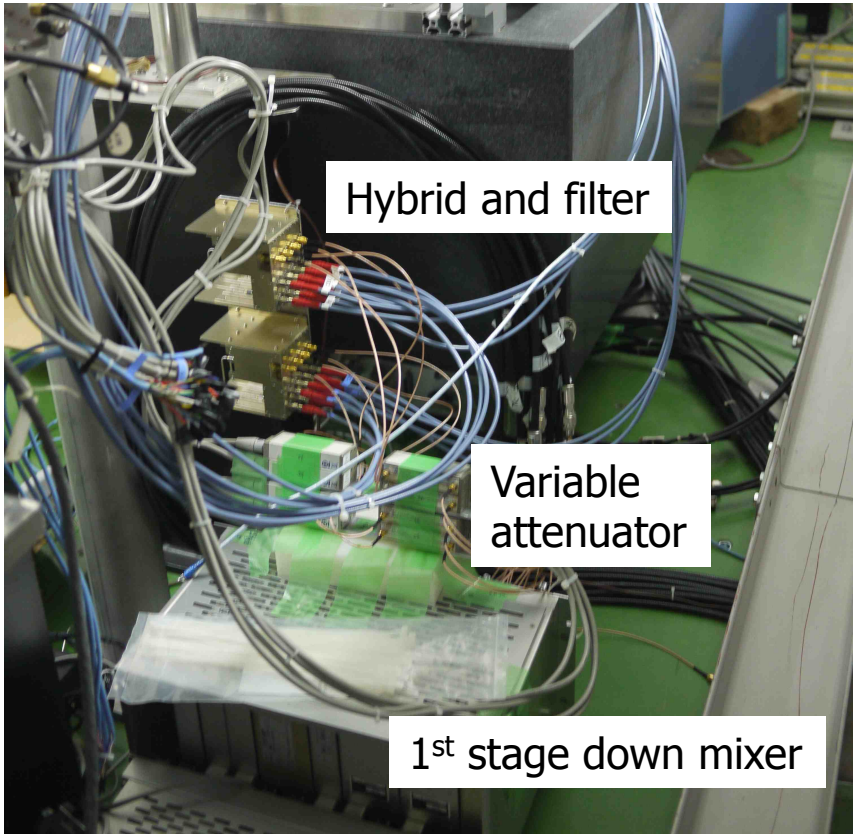
IPBPM location



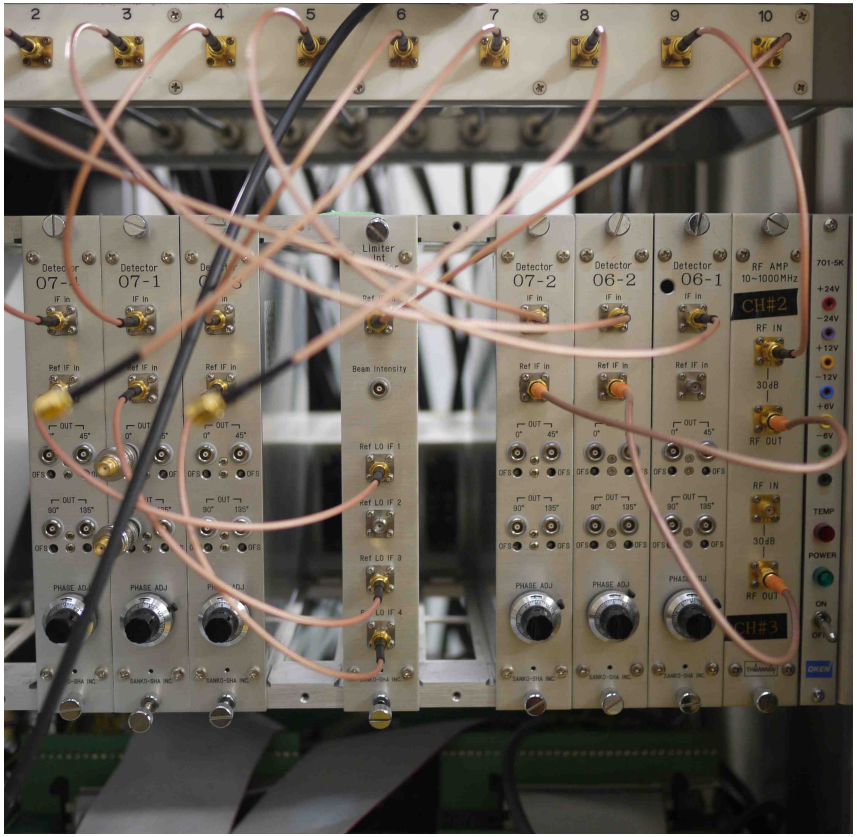


Hardware installation

First stage of down mixer (C-band - > 714 MHz)
@ in the tunnel

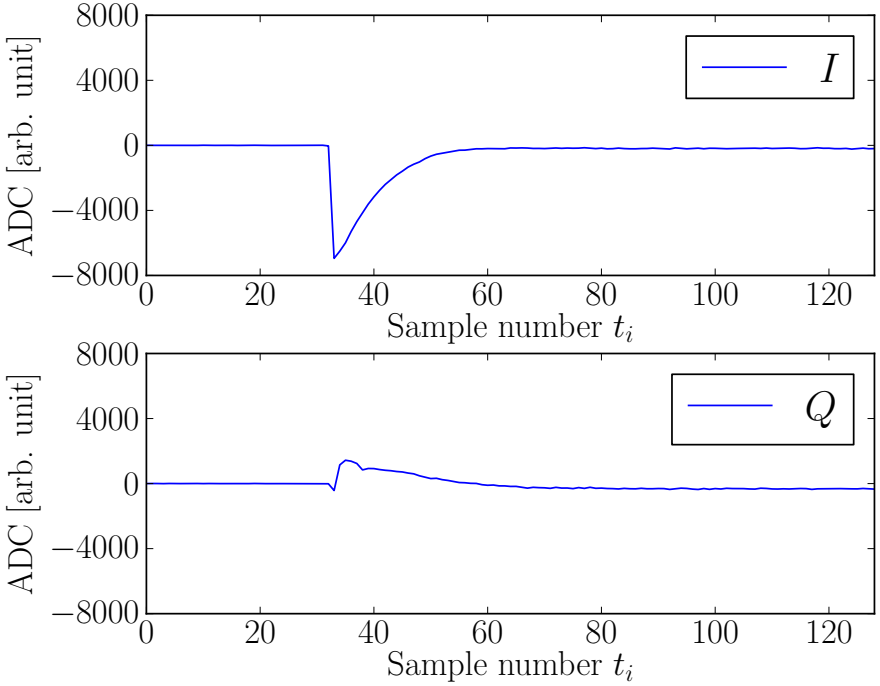


Second stage of down mixer (714 MHz -> I, Q)
@ the outside of the tunnel

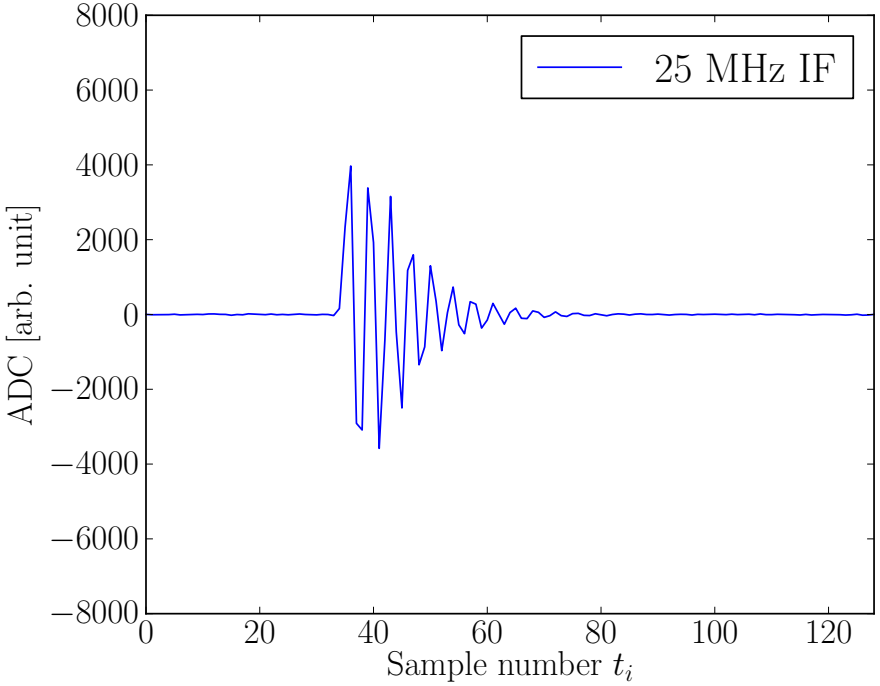


Digitised signals

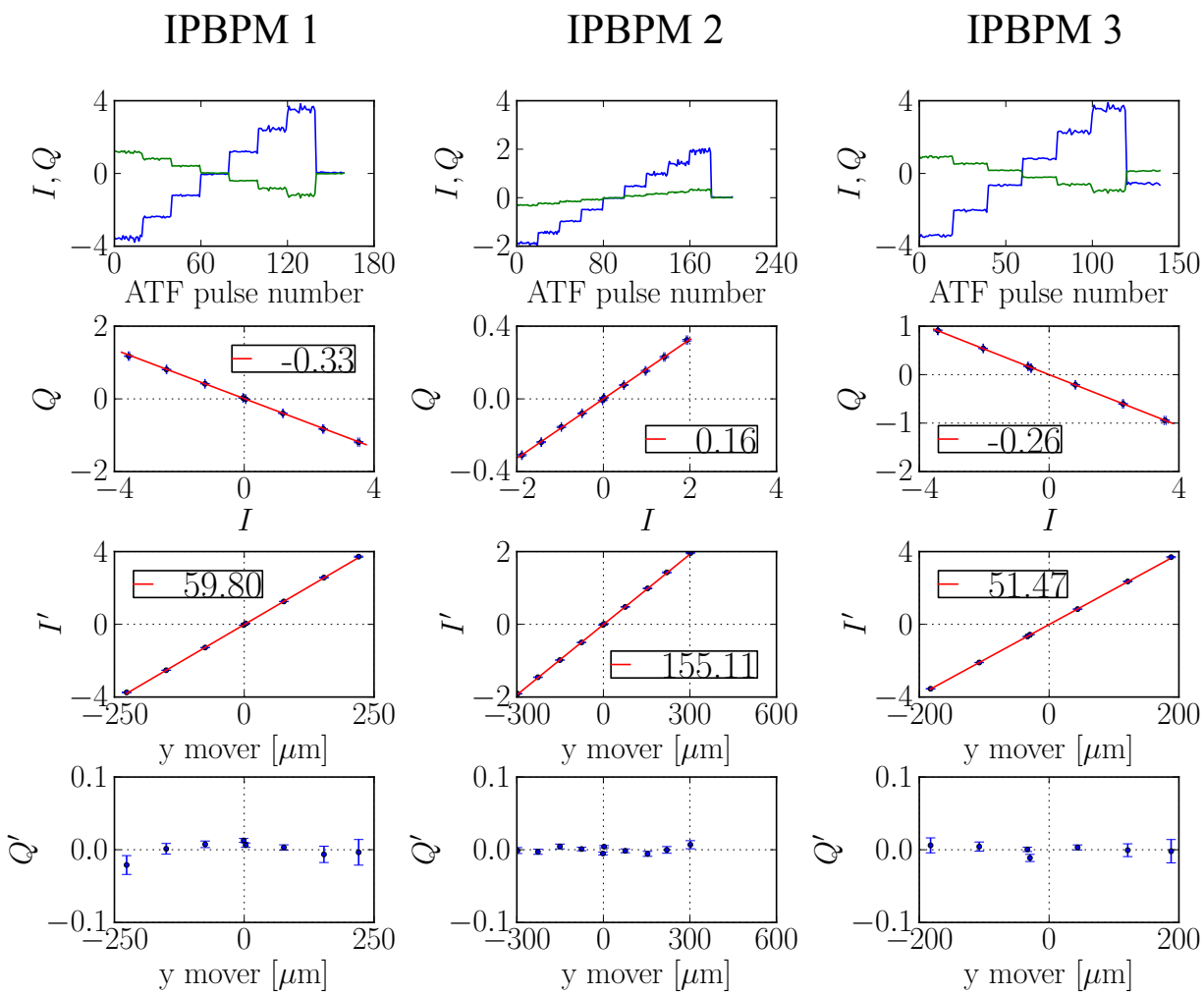
Homodyne processing (Zero IF)



Heterodyne processing (Nonzero IF)



Calibration



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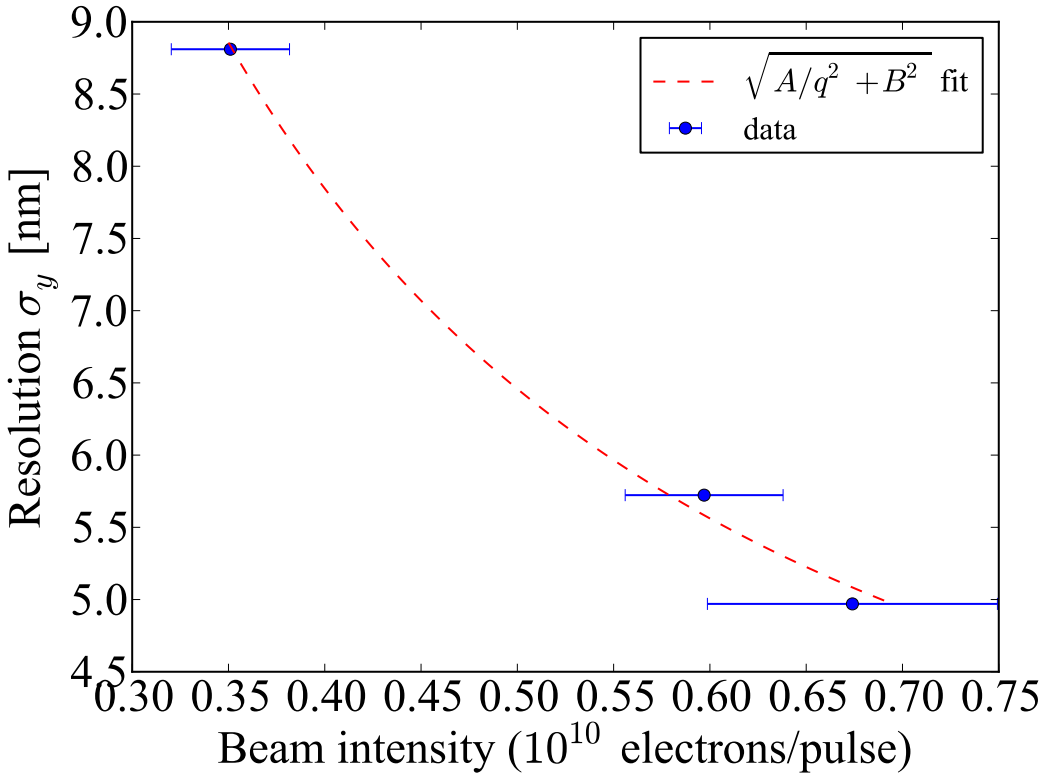
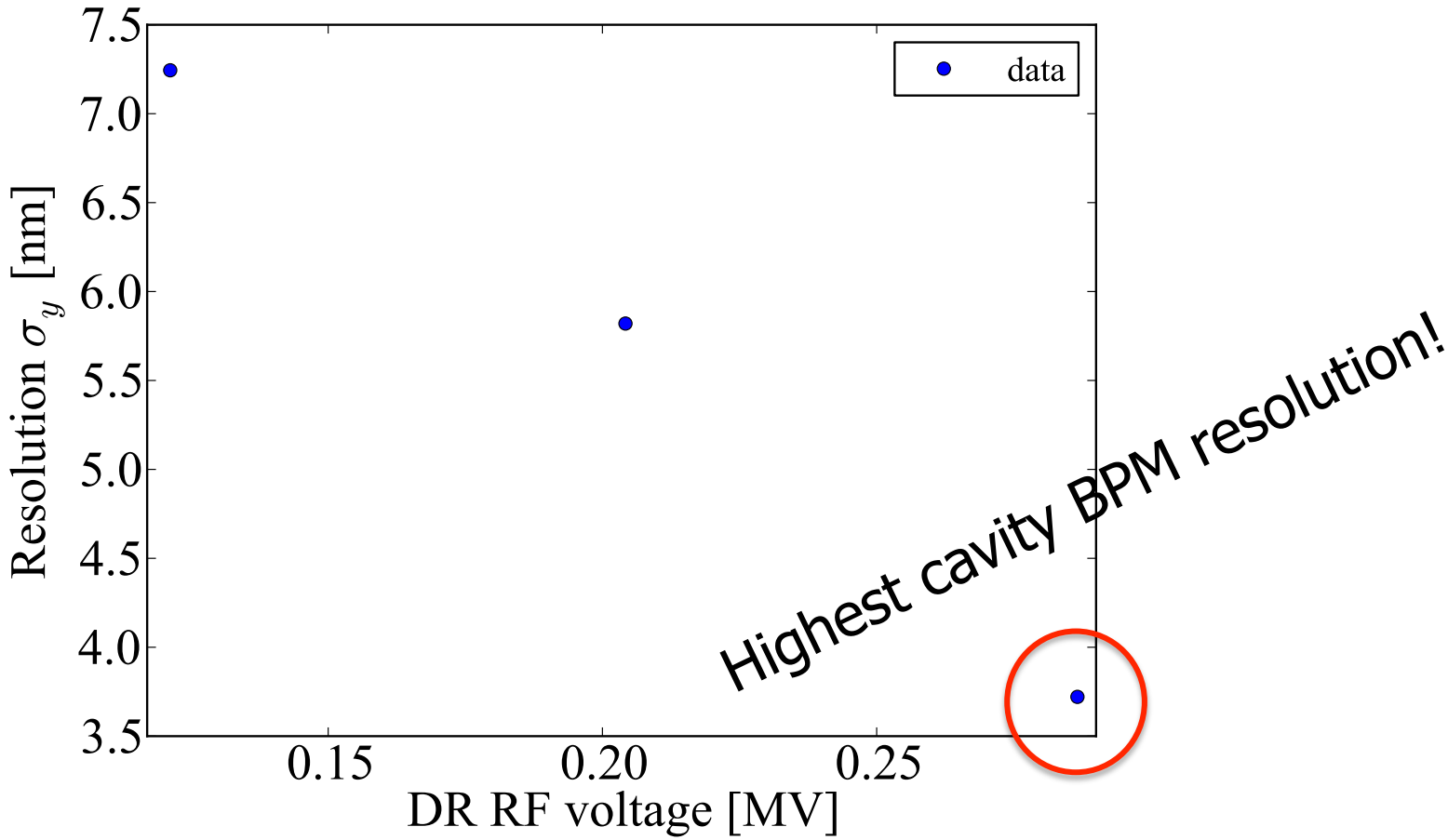
$$y = \frac{dY_{mover}}{dI'} \cdot I'$$

Resolution



The resolution varies between 9.5 and 5.5 nm with typical ATF2 beam intensities. Given the fit parameters the vertical resolution with 2×10^{10} electrons is 3 nm.

Resolution


7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
Resolution σ_y [nm]
0.15
0.20
0.25
DR RF voltage [MV]
data
Highest cavity BPM resolution!

Accelerator Test Facility (KEK)

- Located at KEK in Tsukuba, Japan
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  - Designed to achieve super-low beam emittance
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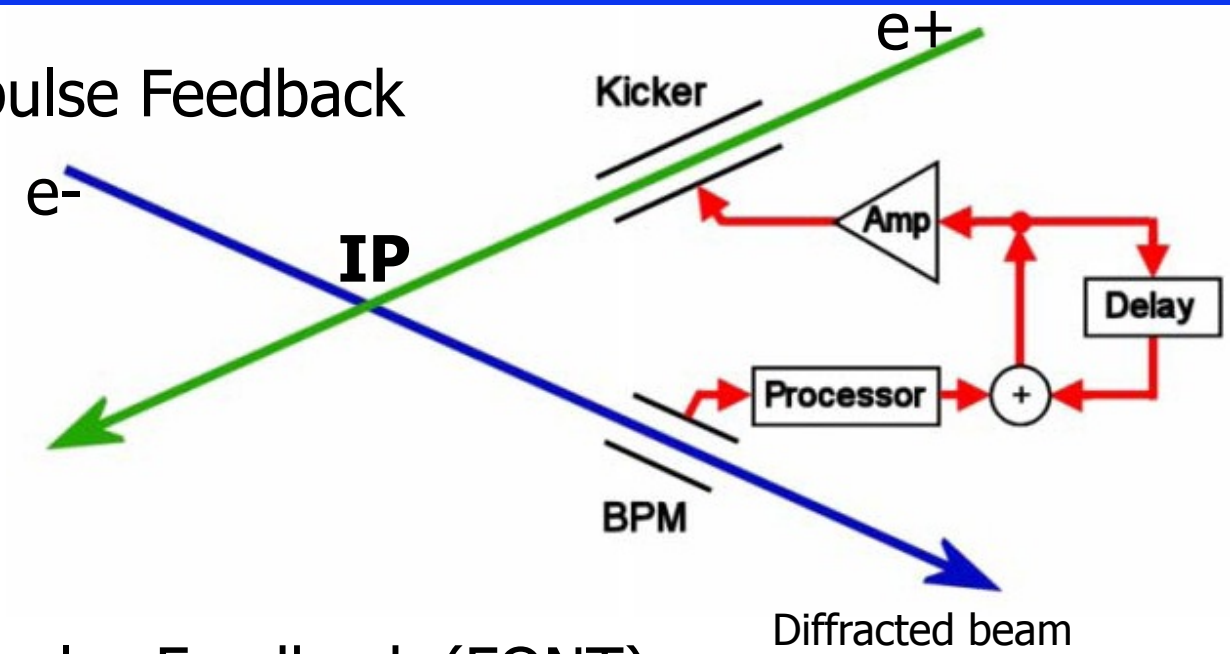
  - Goal 2: Stabilize beam at final focus with 2 nm precision
- Operation rate 1.56 Hz (recently doubled to 3.12 Hz)
- Multi-bunch trains
  - Bunch spacing 150 – 300 ns

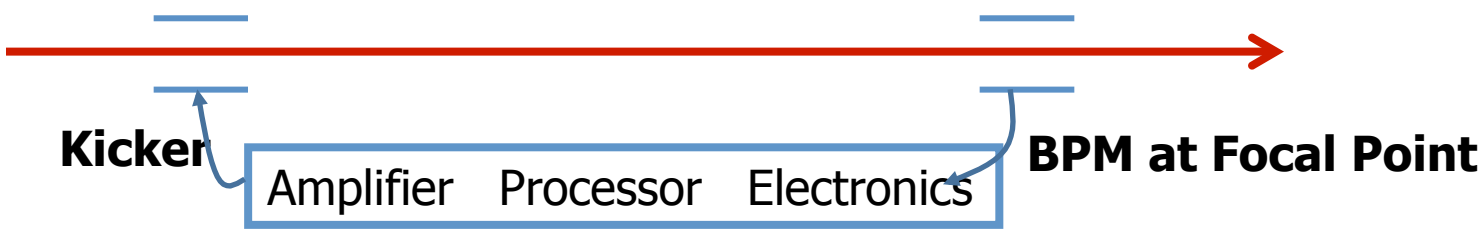
Goal2: Beam position control in 2 nm by intra-pulse feedback

ILC intra-pulse Feedback



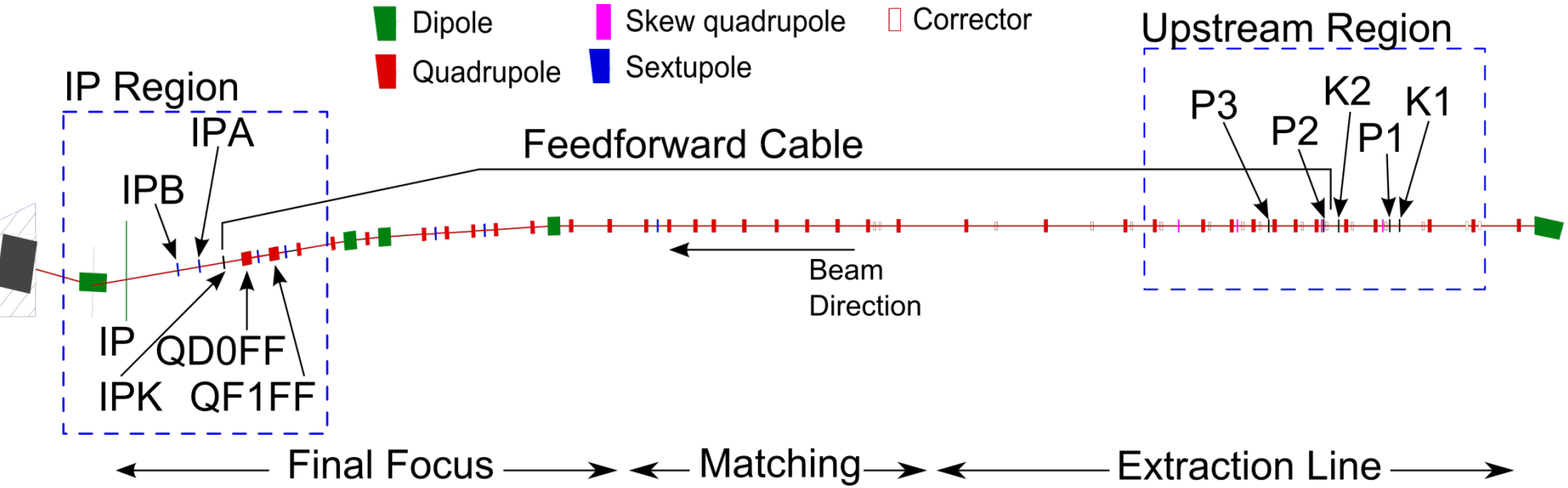
ATF2 intra-pulse Feedback (FONT)

3 bunches/pulse 150 ns spacing or 2 bunches/pulse 230 ns spacing



BPM resolution must be 2 nm, much better than required in ILC (~ micron).

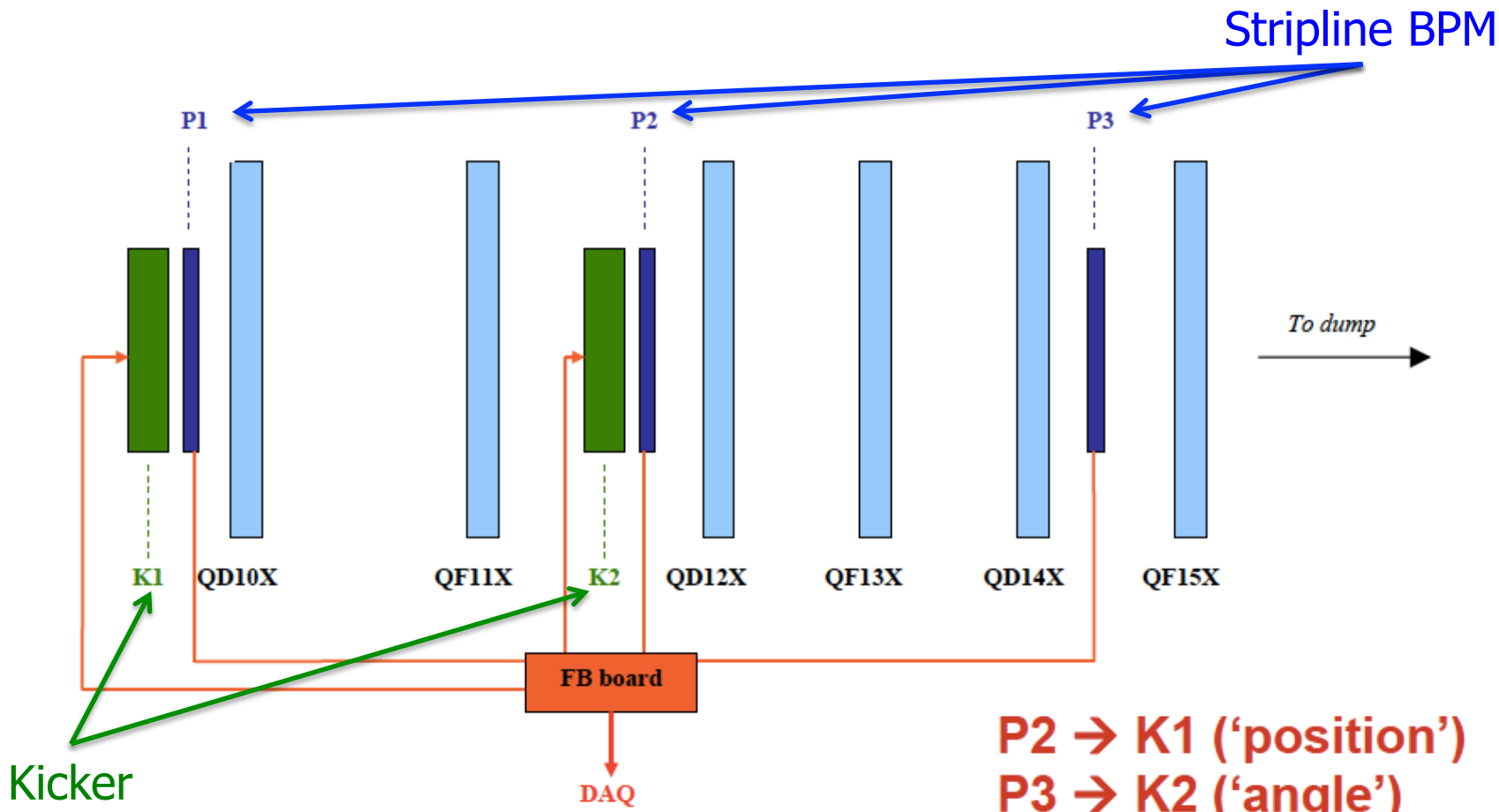
FONT5 operation at ATF2



Aim to stabilise beam in IP region using 2-bunch spill:

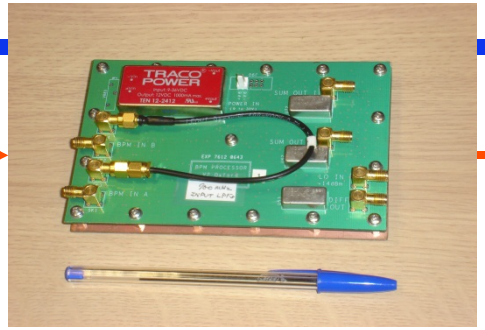
1. Upstream FB: monitor beam at IP
2. Feed-forward from upstream BPMs → IP kicker
3. Local IP FB using IPBPM signal and IP kicker

FONT upstream operation mode



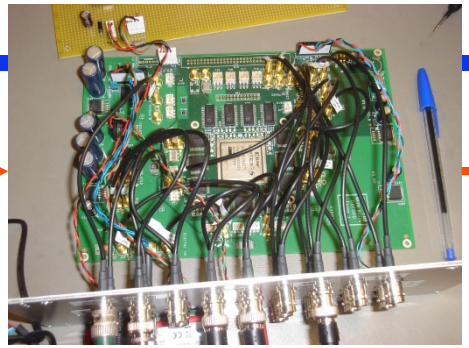
P2 → K1 ('position')
P3 → K2 ('angle')
P3 → K1

Upstream FONT5 System



Analogue Front-end

BPM processor

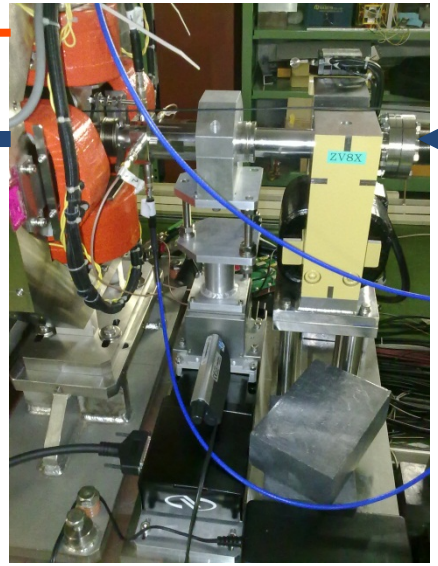


FPGA-based digital processor

Kicker drive amplifier

Strip-line kicker

Beam

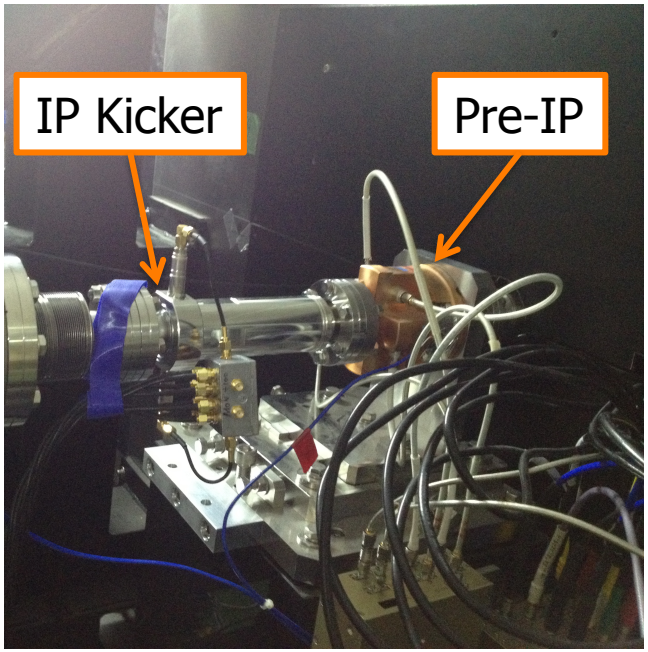


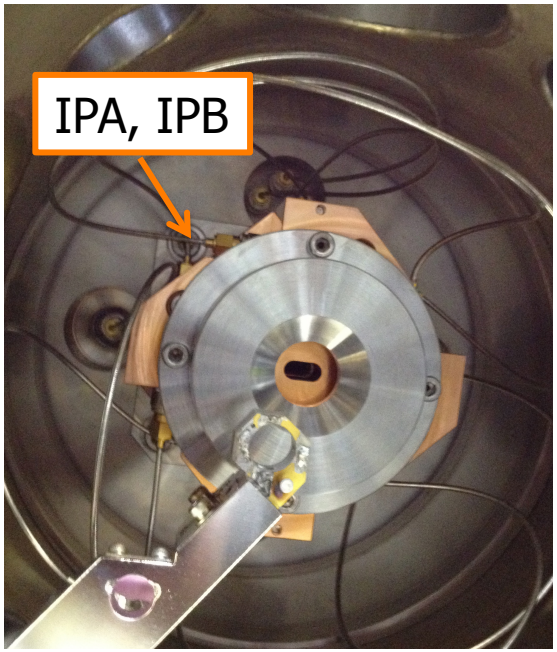
Stripline BPM with mover system

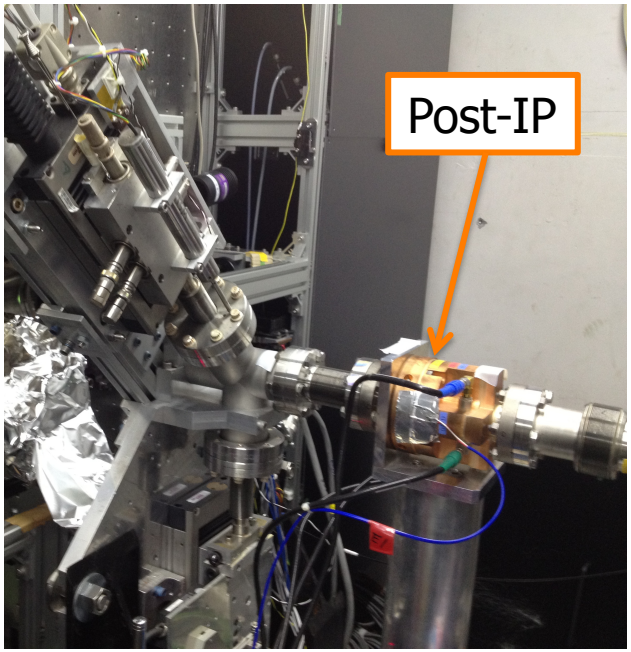
BPM Resolution	Sub micron
Dynamic range of the BPM system	+/-500µm
System Latency	<150 ns
Amplifier Bandwidth	~30 MHz

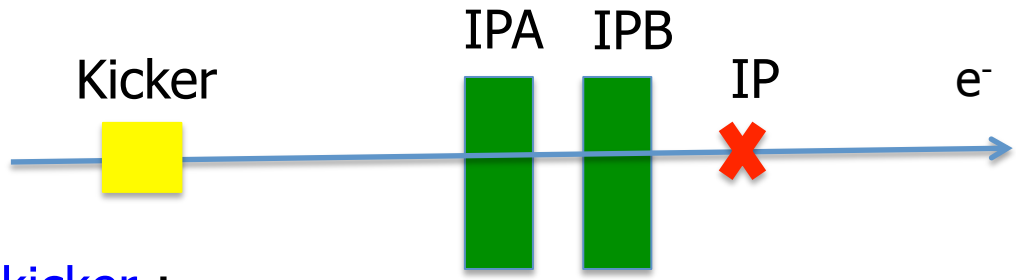
IP area

e^-







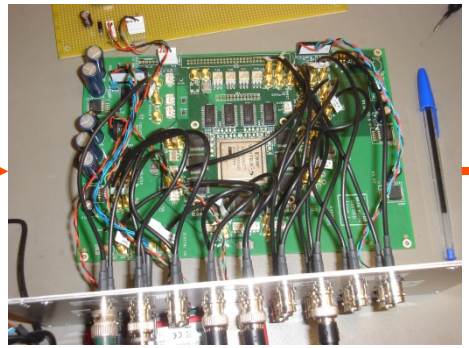


New IP kicker :
Designed by Oxford, fabricated and arranged by KEK, Installed May 2012

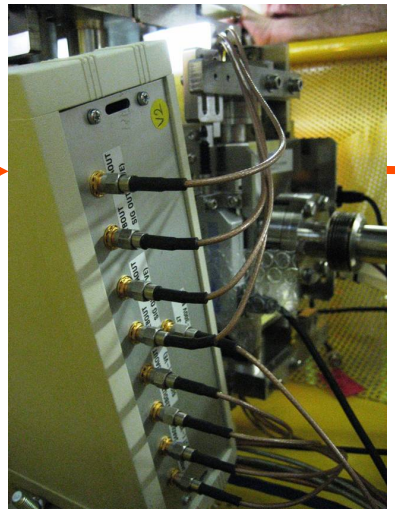
Interaction Point FONT System

Analogue Front-end

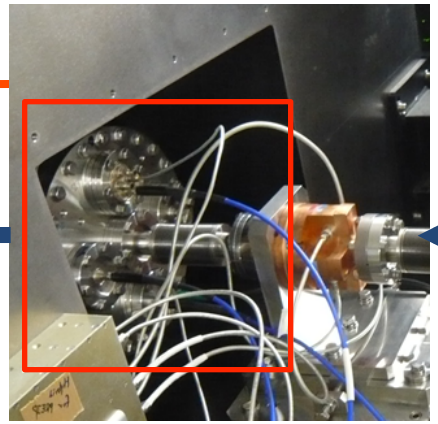
BPM processor



FPGA-based digital processor

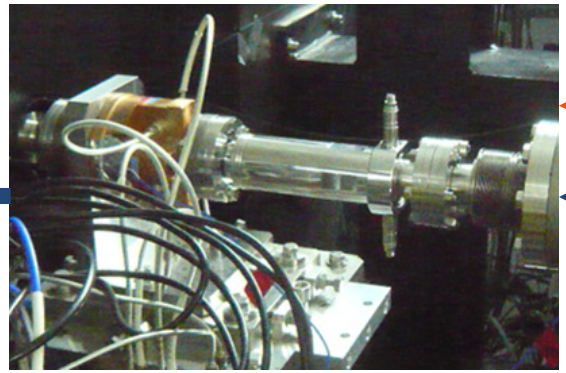


Kicker drive amplifier



Cavity BPM

Beam

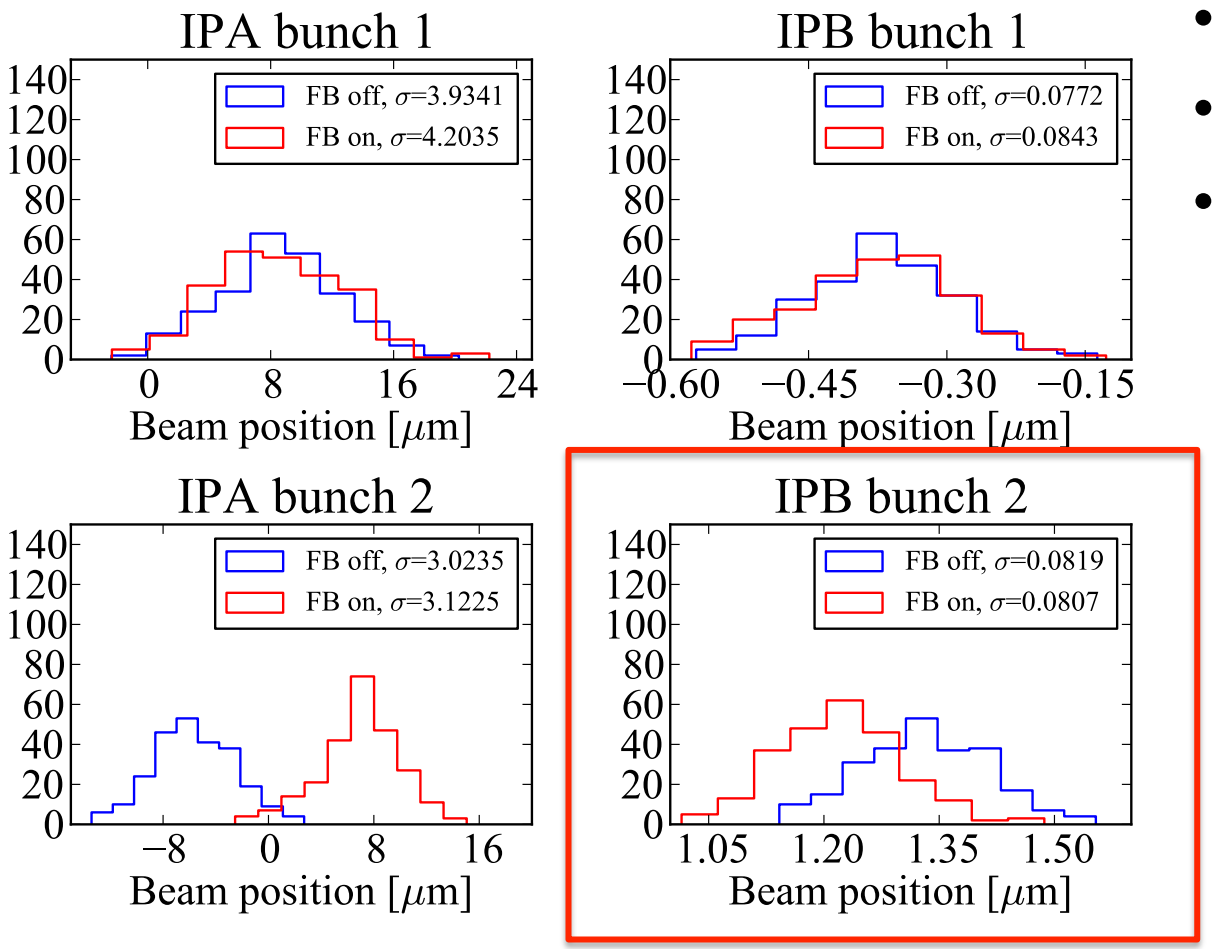


Strip-line kicker

- Designed in house
- 12.5 cm stripline kicker
- Based on ATF stripline BPMs

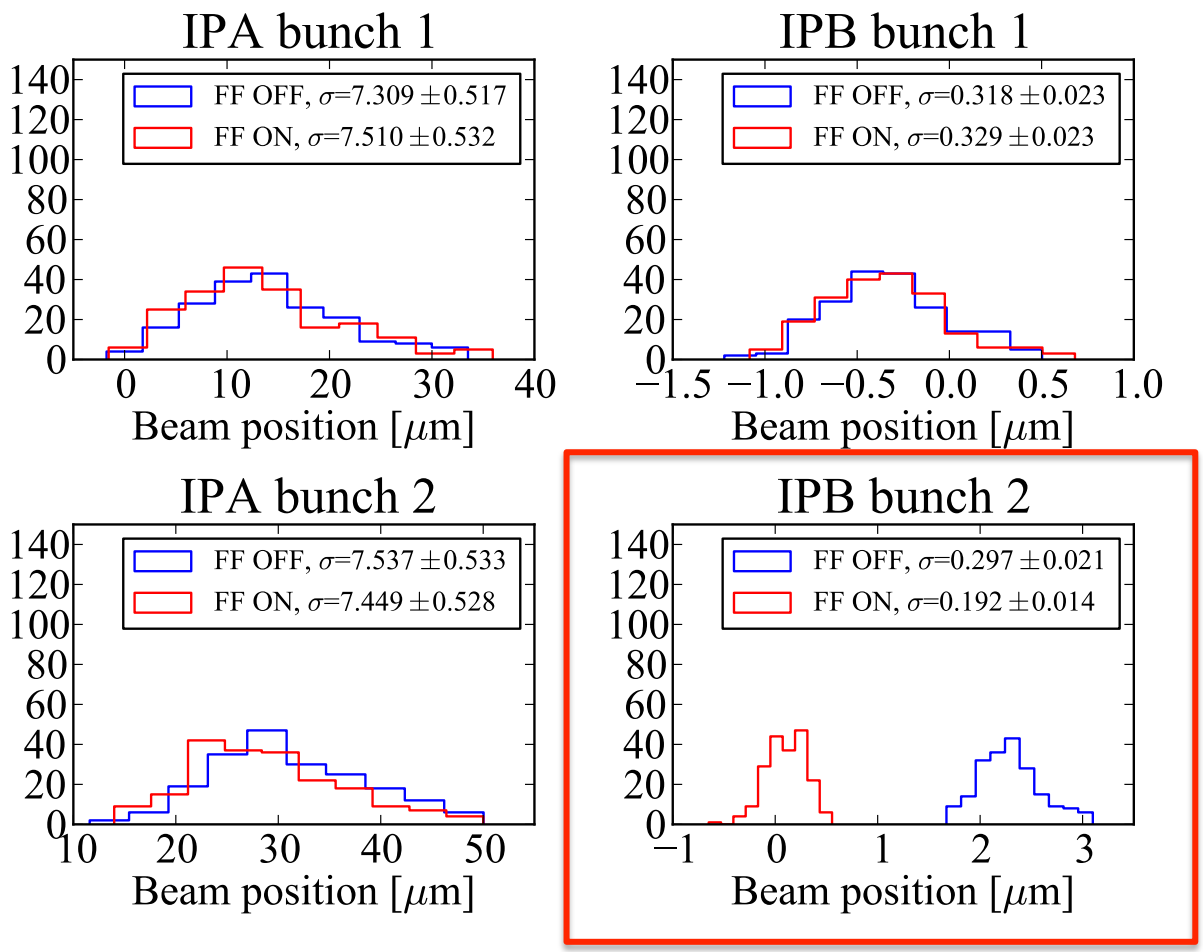
Upstream FB

Observe effect of upstream FB at IP

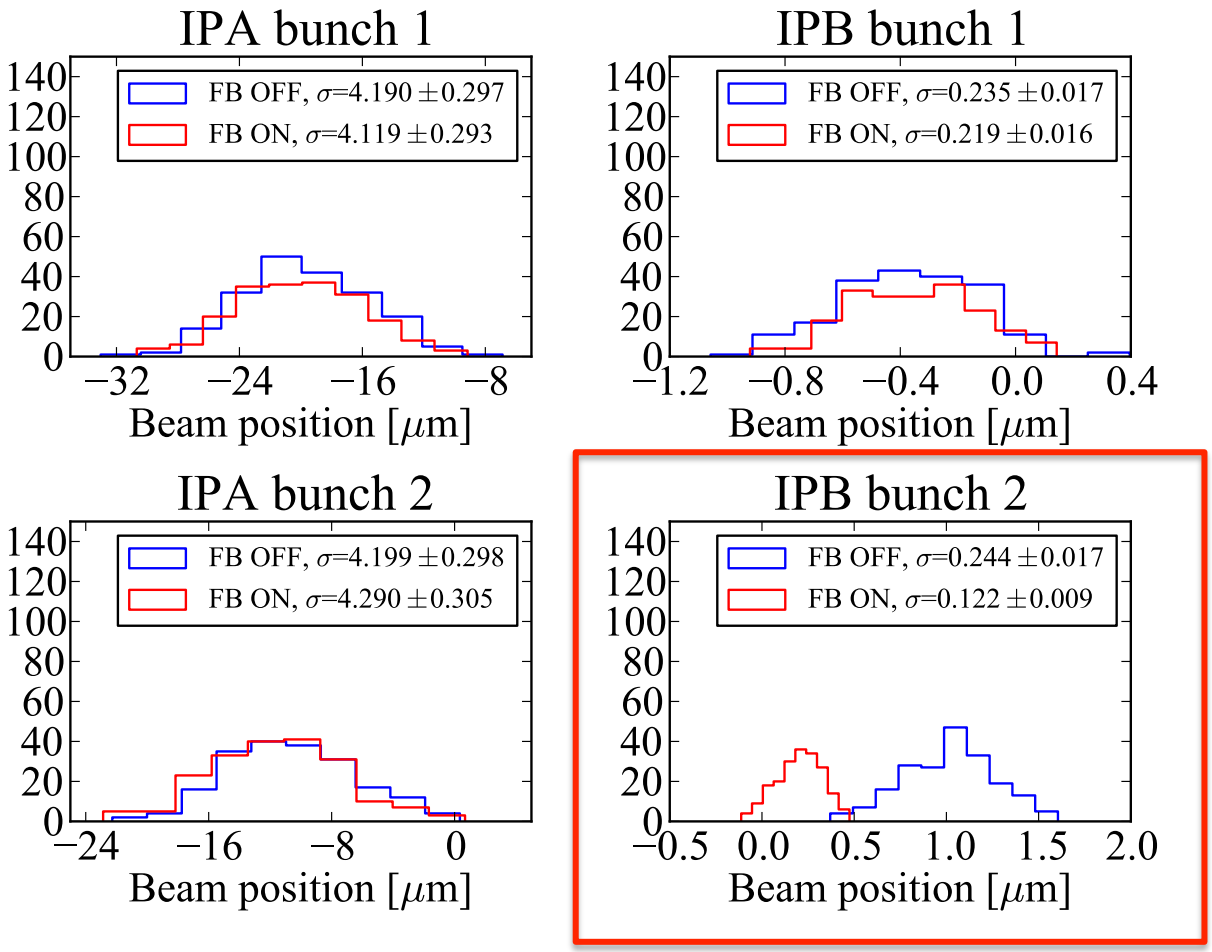


- Measure 1st bunch
- Calculate gain
- Correct 2nd bunch

Feedforward



IP FB


IPA bunch 1
FB OFF, σ=4.190 ±0.297
FB ON, σ=4.119 ±0.293
Beam position [μm]
IPB bunch 1
FB OFF, σ=0.235 ±0.017
FB ON, σ=0.219 ±0.016
Beam position [μm]
IPA bunch 2
FB OFF, σ=4.199 ±0.298
FB ON, σ=4.290 ±0.305
Beam position [μm]
IPB bunch 2
FB OFF, σ=0.244 ±0.017
FB ON, σ=0.122 ±0.009
Beam position [μm]

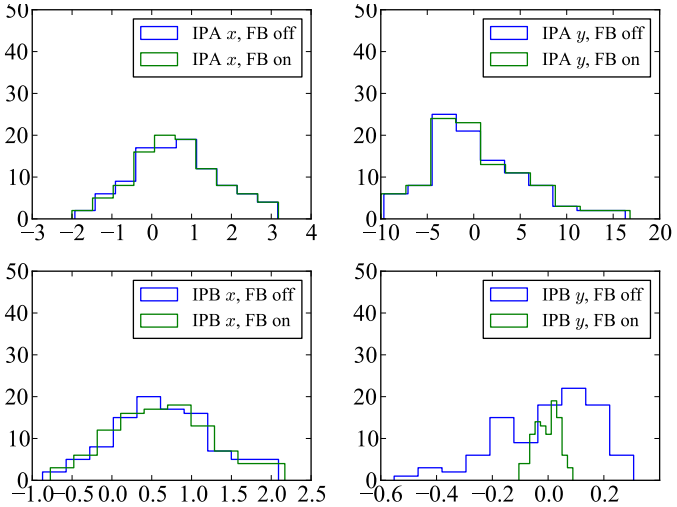
Beam Tracking simulation

- Macropaticle tracking through the BDS using the code PLACET
- For beam dynamics
- Used to help understand IP feedback
- Used to help understand CBPM resolution

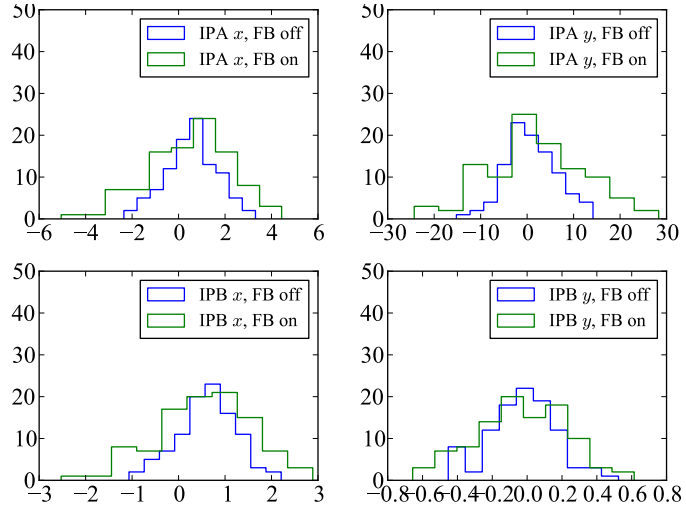
IP Feedback simulation

Waist on IPB (Both x and y)

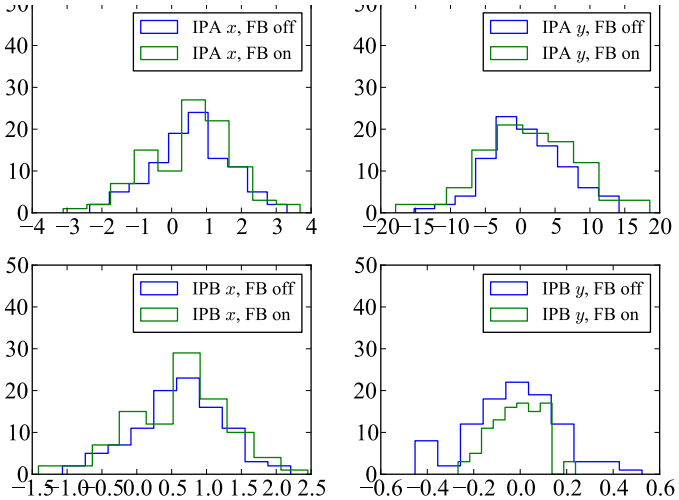
Bunch to bunch correlation on IPB : 97 %



Bunch to bunch correlation on IPB : 57 %



Bunch to bunch correlation on IPB : 87 %



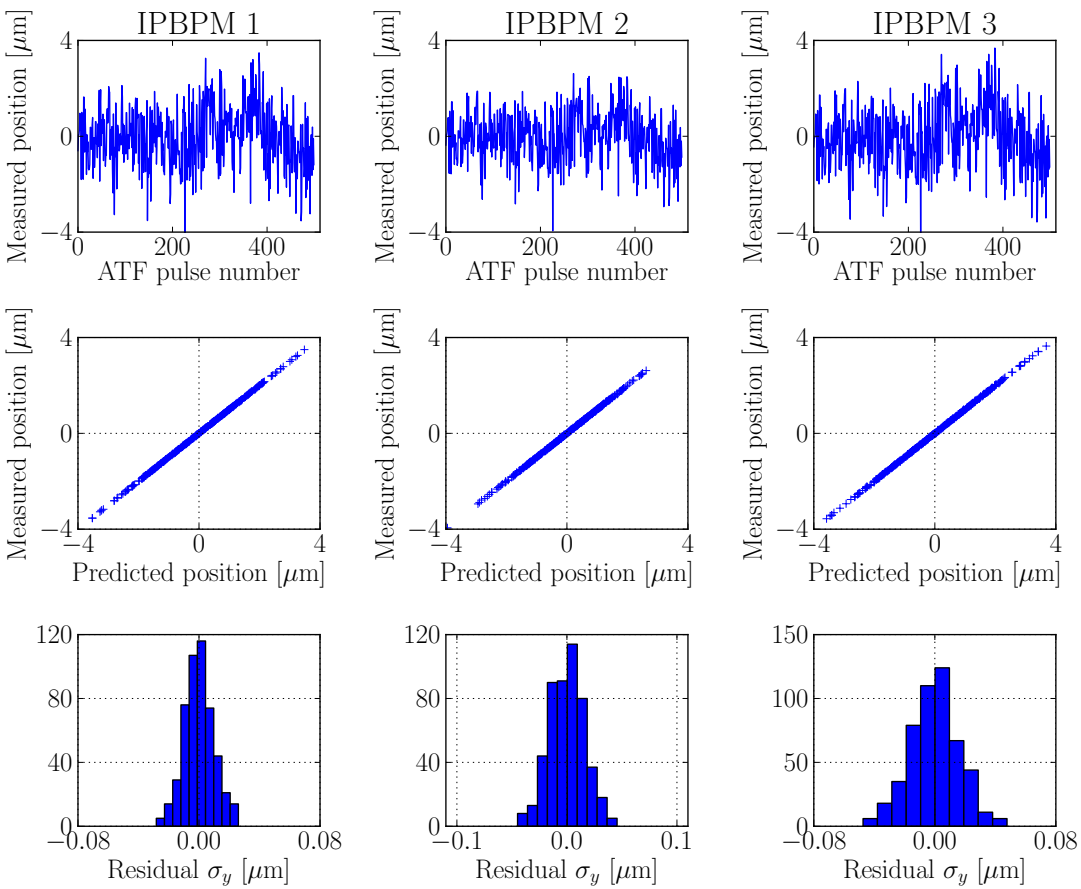
IPBPM resolution : 30 nm

Jitter RMS unit : [nm]

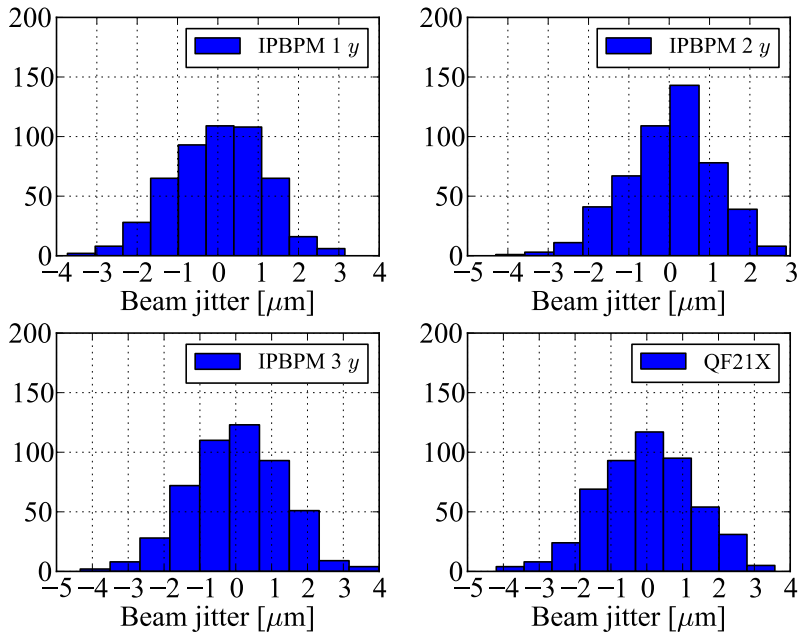
	FB OFF	FB ON
97 %	175	44
87 %	194	104
57 %	194	259

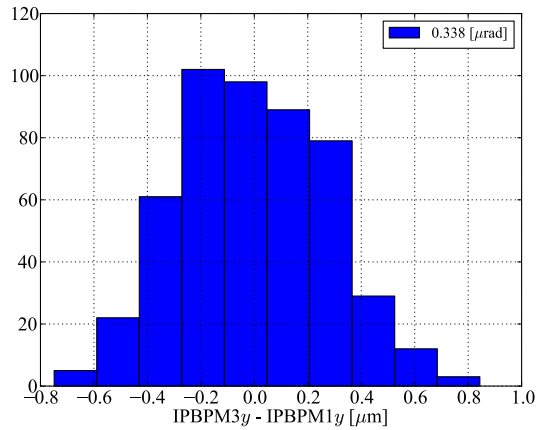
Measurement

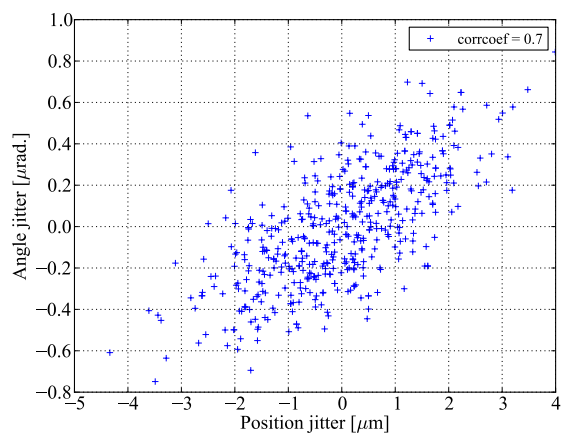
Typical assumption that a triplet of BPMs have same resolution is unrealistic?



Correlation (meas)

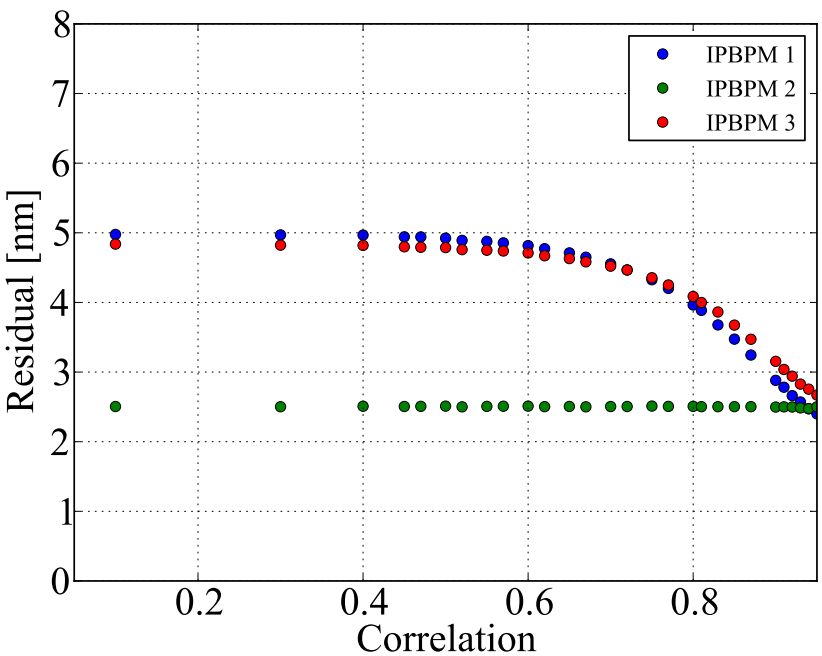




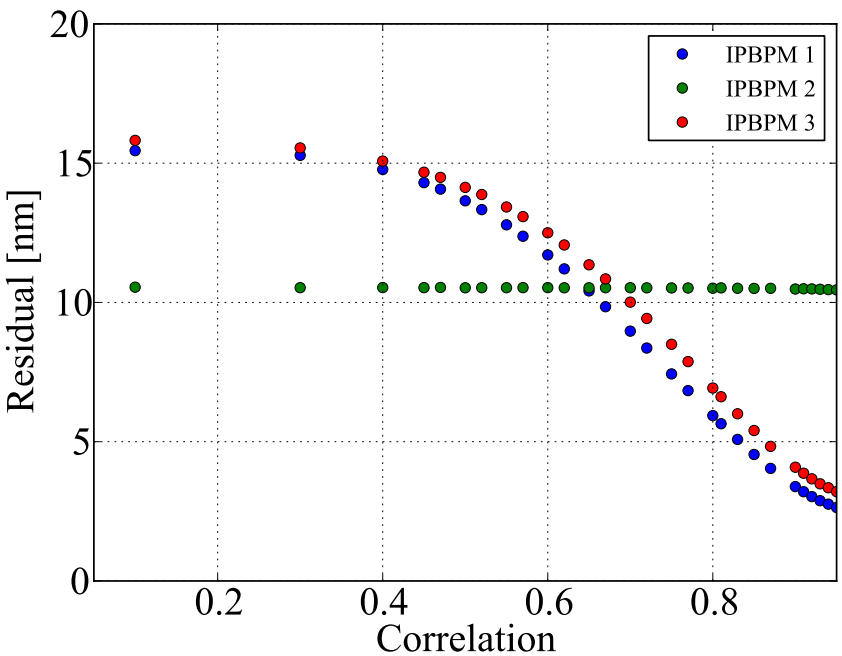


Jitter correlation effect (sim)

All set same resolution : 2 nm



Different resolution set
IPBPM1 : 2 nm
IPBPM2 : 10 nm
IPBPM3 : 2 nm



Summary

- ATF2 cavity BPM system has good and stable resolution
  - Recently published : Phys. Rev. ST Accel. Beams 15, 042801 (2012)
  - Best resolution : 27 nm
- High position sensitivity cavity BPMs system tested at upstream of the ATF2 beam line for the interaction region
  - Homodyne/Heterodyne signal processing methods
  - Best vertical position resolution : 3.6 nm
- Demonstrated feedback using cavity BPM at IP area
- Tracking simulation
  - Feedback is limited by BPM resolution, bunch to bunch correlation
  - Jitter correlation needs to be considered

Backup

Basic principle

$$W = q \int_{\mathbf{s}_1}^{\mathbf{s}_2} \mathbf{E} \cdot d\mathbf{s}$$

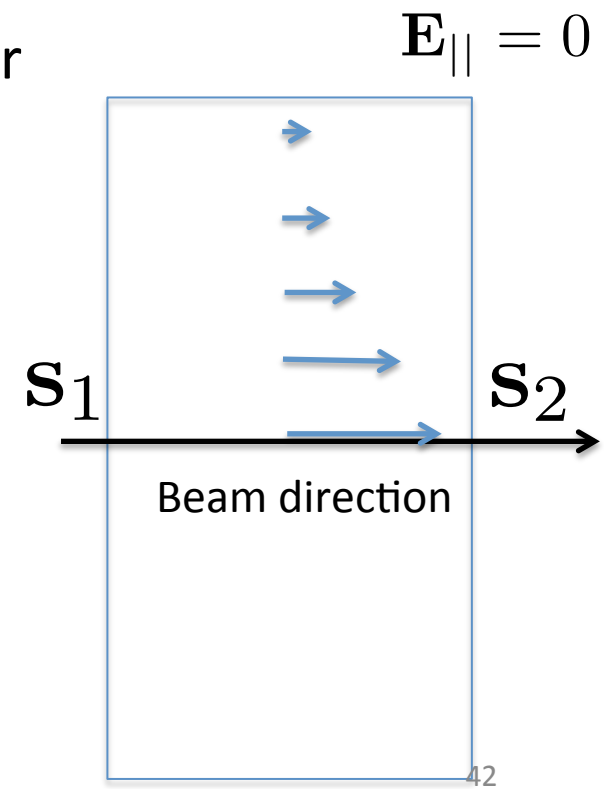
Work done on particle moving in electric field

$$\mathbf{E}_{||} = 0$$

No parallel to conductor Electric field

$$\mathbf{B} \cdot \mathbf{E} = 0$$

Transverse magnetic oscillating electro-magnetic fields



Cavity modes are solution to Maxwell's equations for a cavity

C- and S- band BPMs

TABLE II. Cavity parameters for *C*- and *S*-band devices. Frequencies and isolation measured in air, while Q_L and R/Q are values from electromagnetic simulation.

Parameter	*C*-band	*S*-band
Cavity radius (mm)	26.9	117.6
Cavity length (mm)	12	12
Resonant frequency (GHz)	6.423	2.888
Loaded quality factor Q_L	6000	1800
x-y isolation (dB)	45 (average)	27, 40, 42, 50
Shunt impedance-Q ratio R/Q at 1 mm (Ω)	1.4	0.15
Sensitivity (V/mm/nC)	0.8	0.3

C- and S- band

TABLE III. The rf signal processing electronics parameters.

Parameter	*C*-band	*S*-band
Noise floor, dBm	−93	−80
1 dB compression, dBm	−20	10
Gain, dB	25	10
Bandwidth, MHz	50	50
Noise figure, dB	11	18
X-*Y* cross talk, dB	−59	NA

IPBPMs

Parameters	f_d [GHz]	β	Q_L	Q_0	Q_{ext}	$(R/Q)_0$ @ 1mm offset	τ [ns]
x dipole	5.7086	1.4	2070	5337	3382	0.549	58
y dipole	6.4336	2.0	1207	5015	1590	1.598	30

Table 1. Simulated parameters of the CBPMs [8].

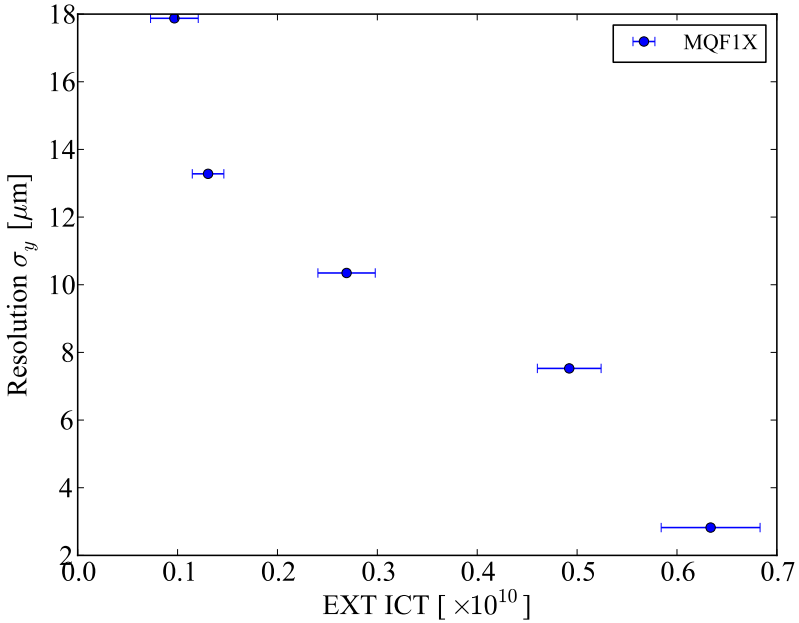
Parameter	Noise floor [dBm]	P1dB [dBm]	Gain [dB]	Bandwidth [MHz]	Noise figure [dB]
x and y	-95	16	35	100	1.7

Table 3. RF signal processing electronics parameters of the IPBPM.

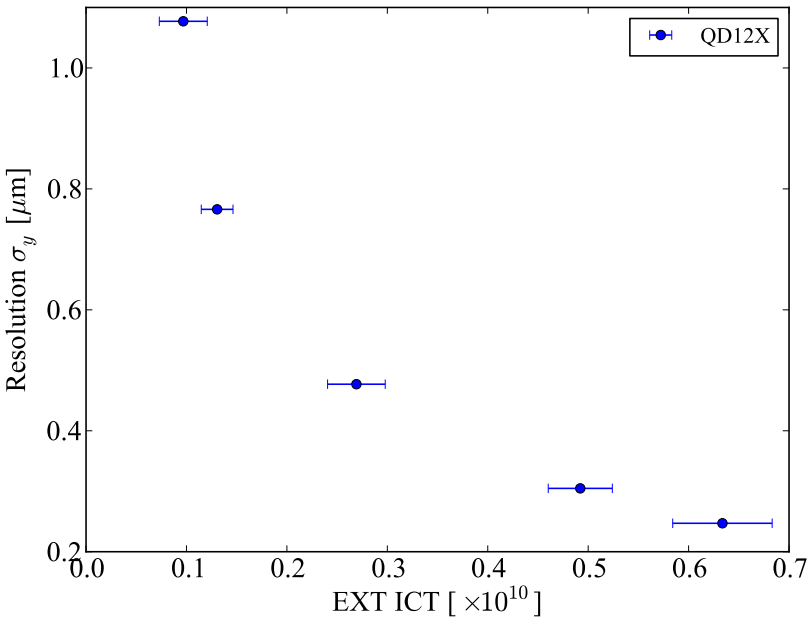
C-band BPM

Resolution vs. Intensity (2013)

Stripline BPM

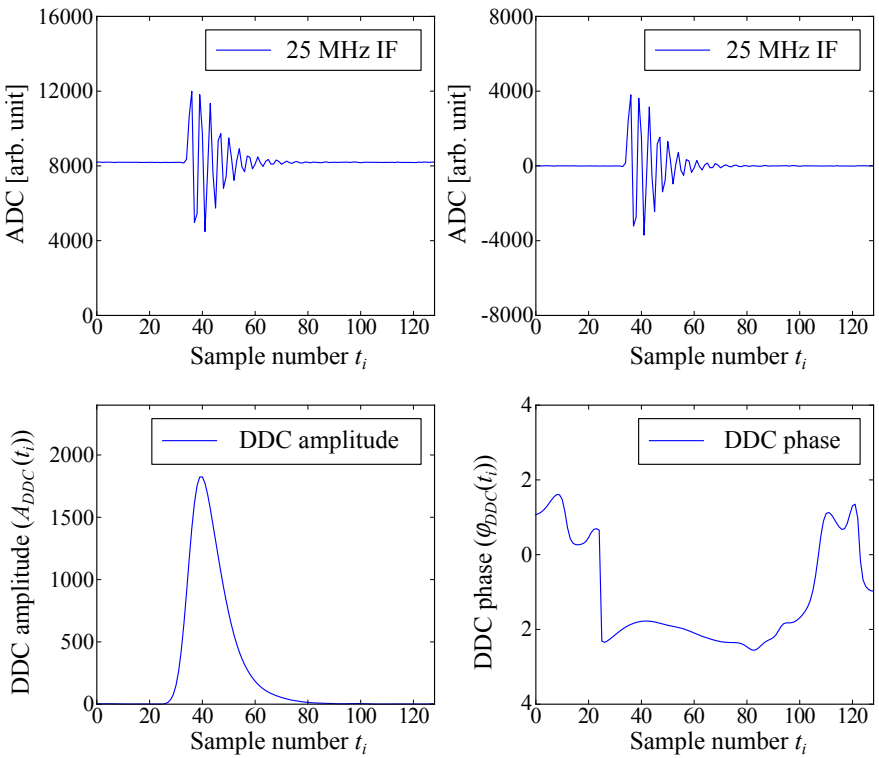


Cavity BPM with 20 dB attenuator

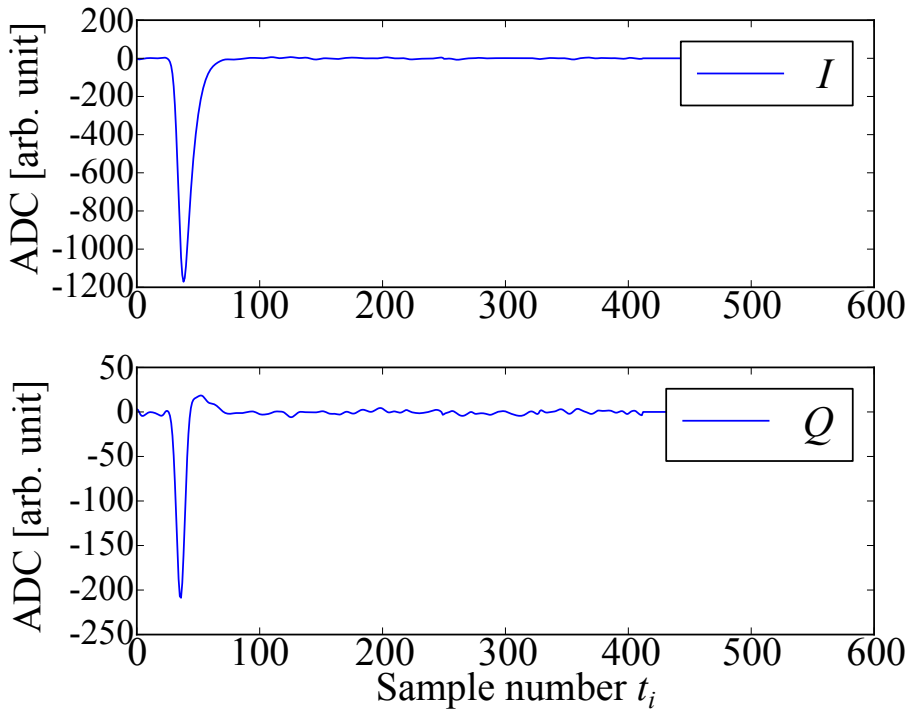


Digital signal processing

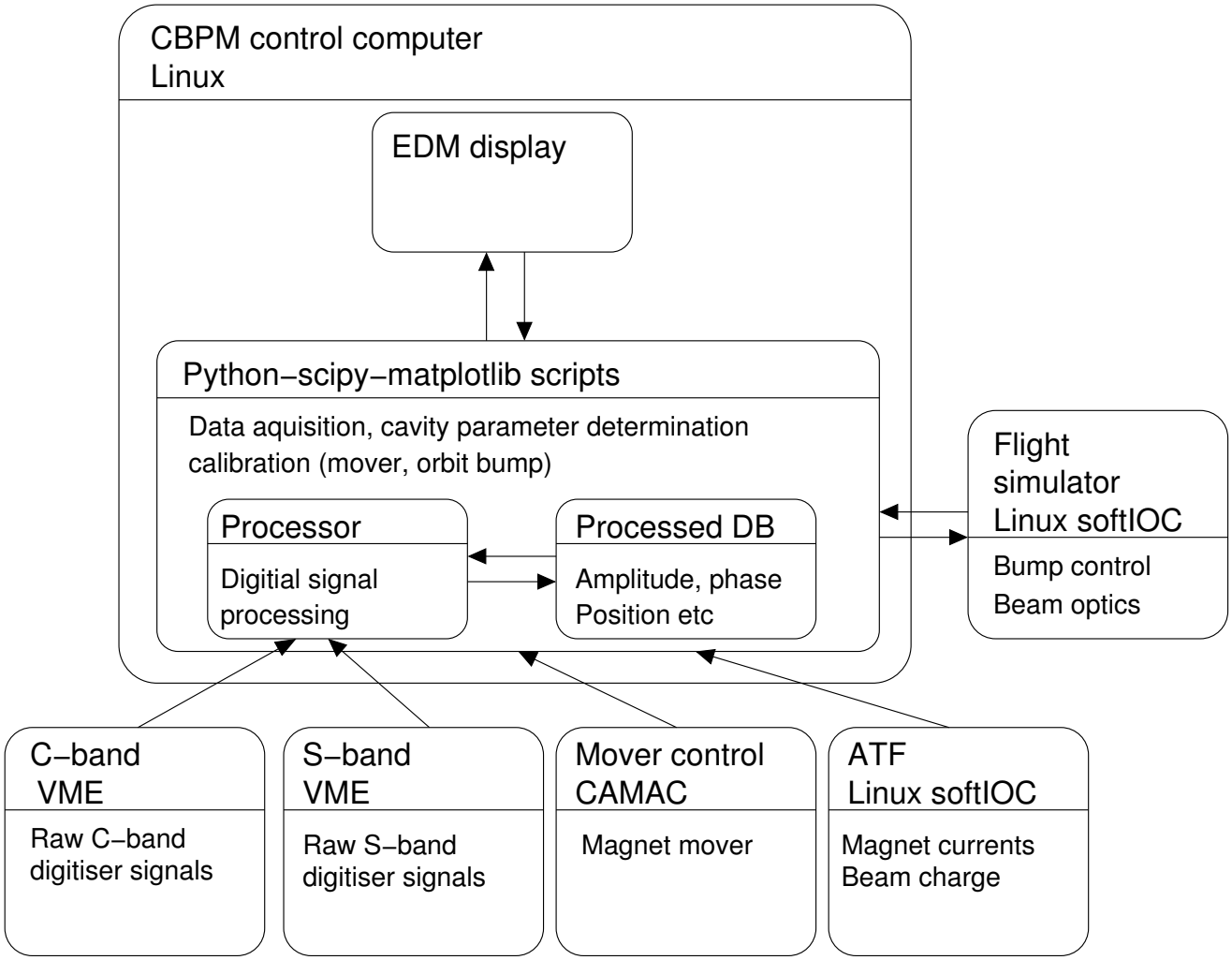
Digital Down-Conversion (DDC)



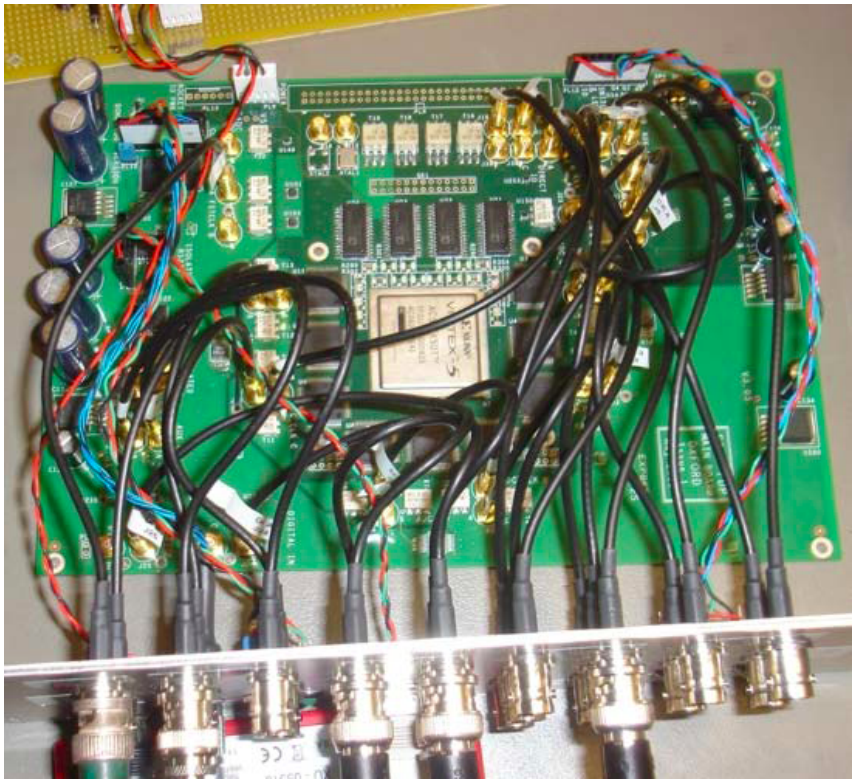
Reconstructed I and Q



CBPM software



FONT5 FB board



- Xilinx Virtex5 FPGA
- 9 ADC input channels
  - TI ADS5474
- 4 DAC output channels
  - AD9744
- Clocked at 357 MHz phase-locked to beam
- 4x faster than FONT4

Latency estimate

- 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

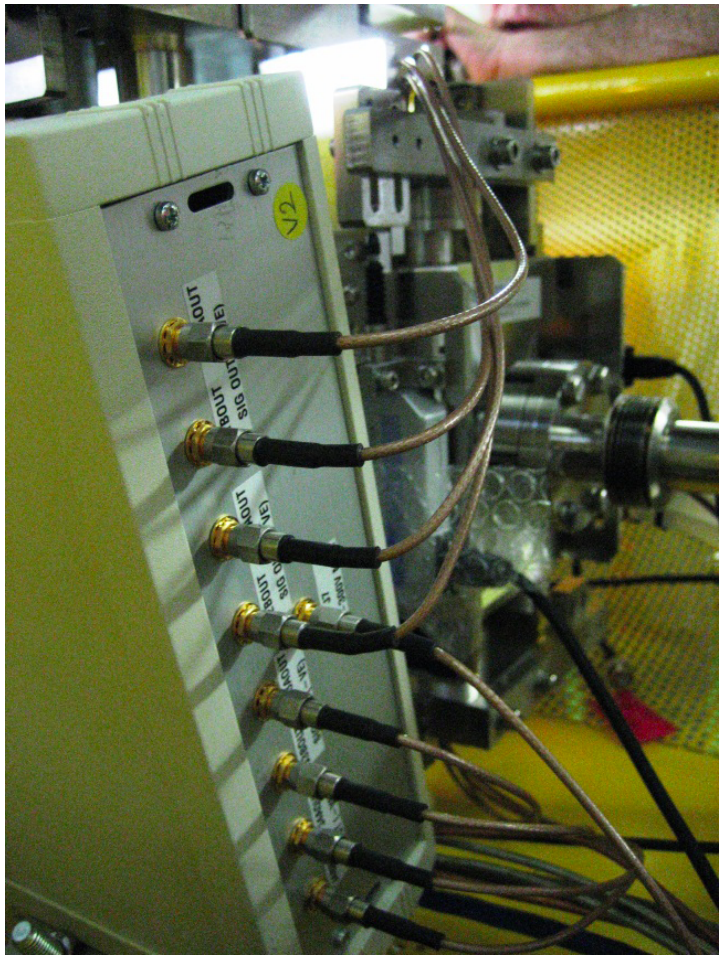
  Electronics latency: 87ns

- Total latency budget: 131ns

Kicker driver amplifier

- +-15A (kicker terminated w/ 50 Ohm
- +- 30A (kicker shorted at far end)
- 35 ns risetime (to 90%)
- Pulse length 10 us (specified for 20-60 bunches)
- Repetition rate 10 Hz

- Outline design done in Oxford
- Order placed w/ TMD Technologies



Default parameters

- Energy : 1.3 GeV
- Bunch length : 8 mm
- Energy spread : 0.08
- Normalised emittance x/y : 5200/30 (nm)
- BPM resolution
  - Stripline : 1 um
  - FONT stripline : 0.5
  - C-band : 200 nm
  - C-band without attenuation : 50 nm
  - S-band : 1 um
  - IPBPM : 100 nm

Options

- Multipole components (all magnets) on/off
- Sextupole on/off
- Wakefield
- Ground motion
- x-y coupling
- Multi bunch
  - Bunch to bunch correlation
- Jitter
  - Beam jitter
  - Bunch jitter
  - Kicker jitter
  - Magnet jitter
- IP + FONT area Feedback

Multi bunch

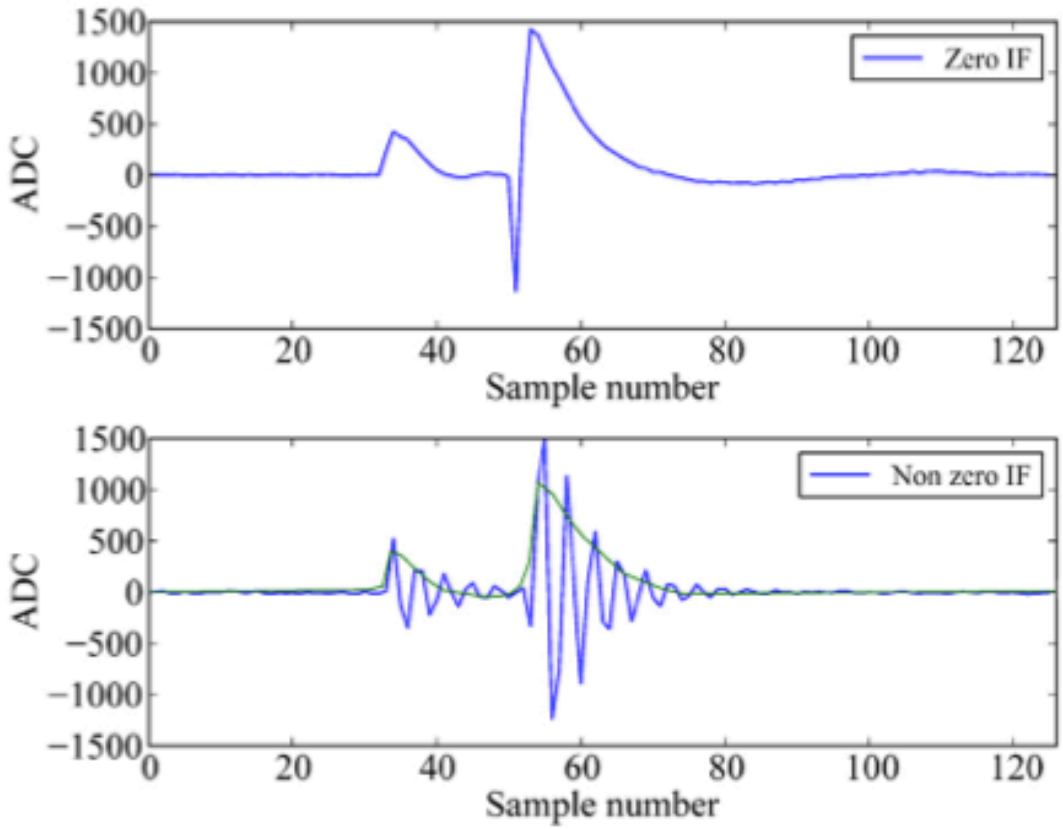


Figure 3: An example of the raw zero and nonzero IF frequency digitised waveforms from the IPBPM electronics in two bunch operation. Green trace is DDC amplitude.