Beam monitors in J-PARC

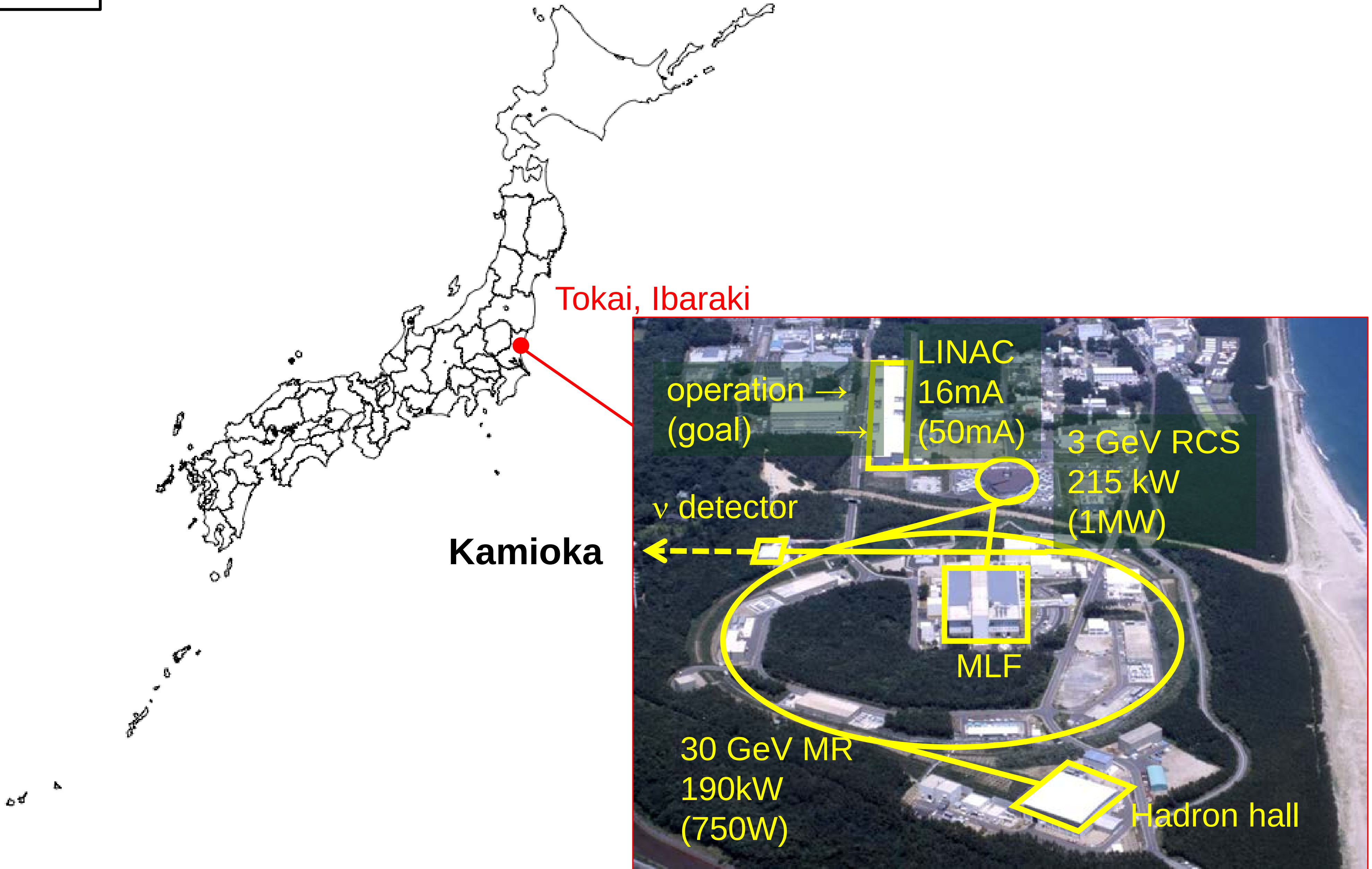
KEK, Accelerator division
H. Kuboki

- Introduction: Beam Monitors in J-PARC
- BPM system in J-PARC Main Ring
- BPM gain calibration (Beam Based Gain Calibration (BBGC))

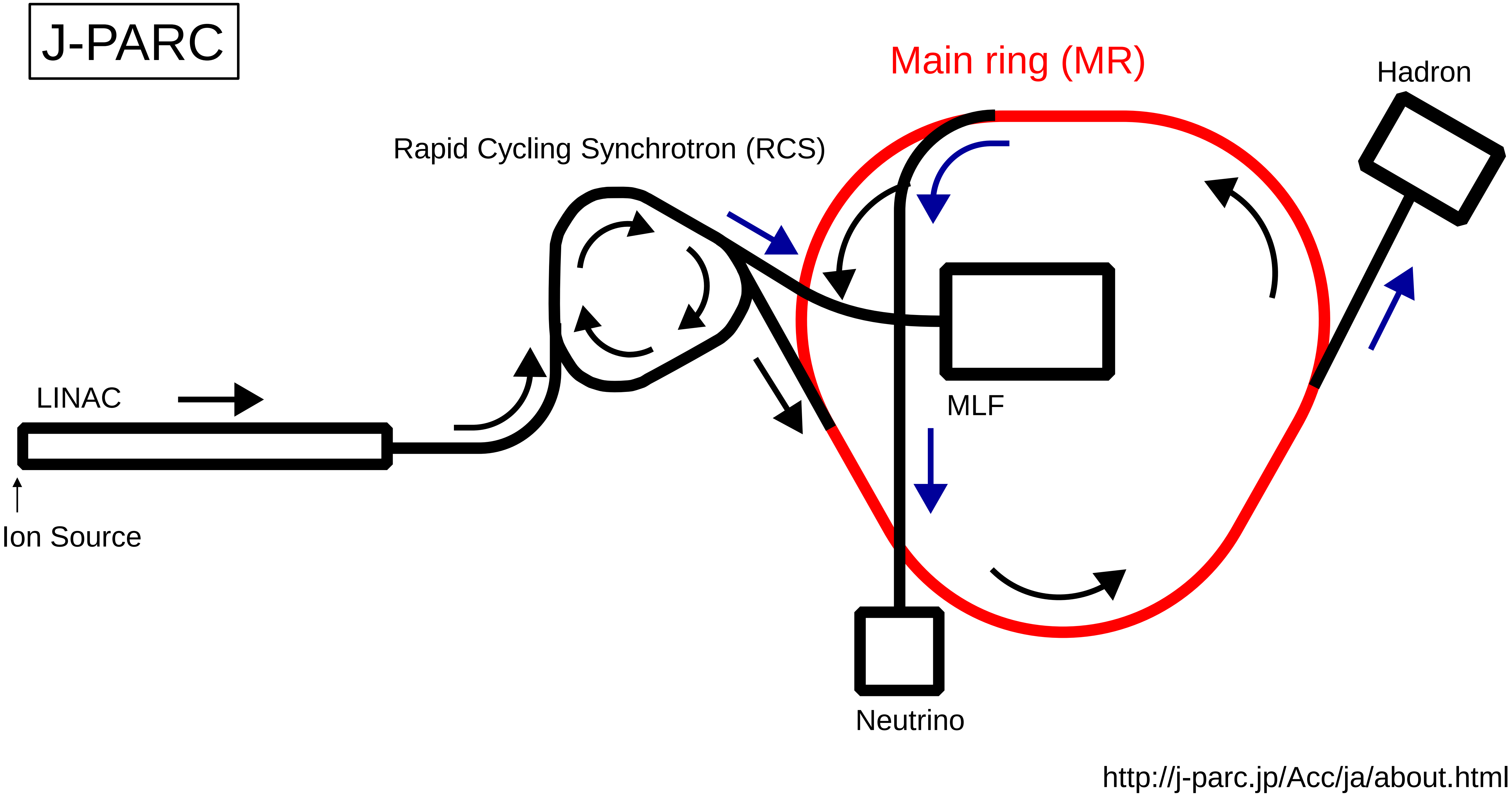
T. Toyama, S. Hatakeyama[A], J. Takano, M. Tejima

KEK, [A]JAEA

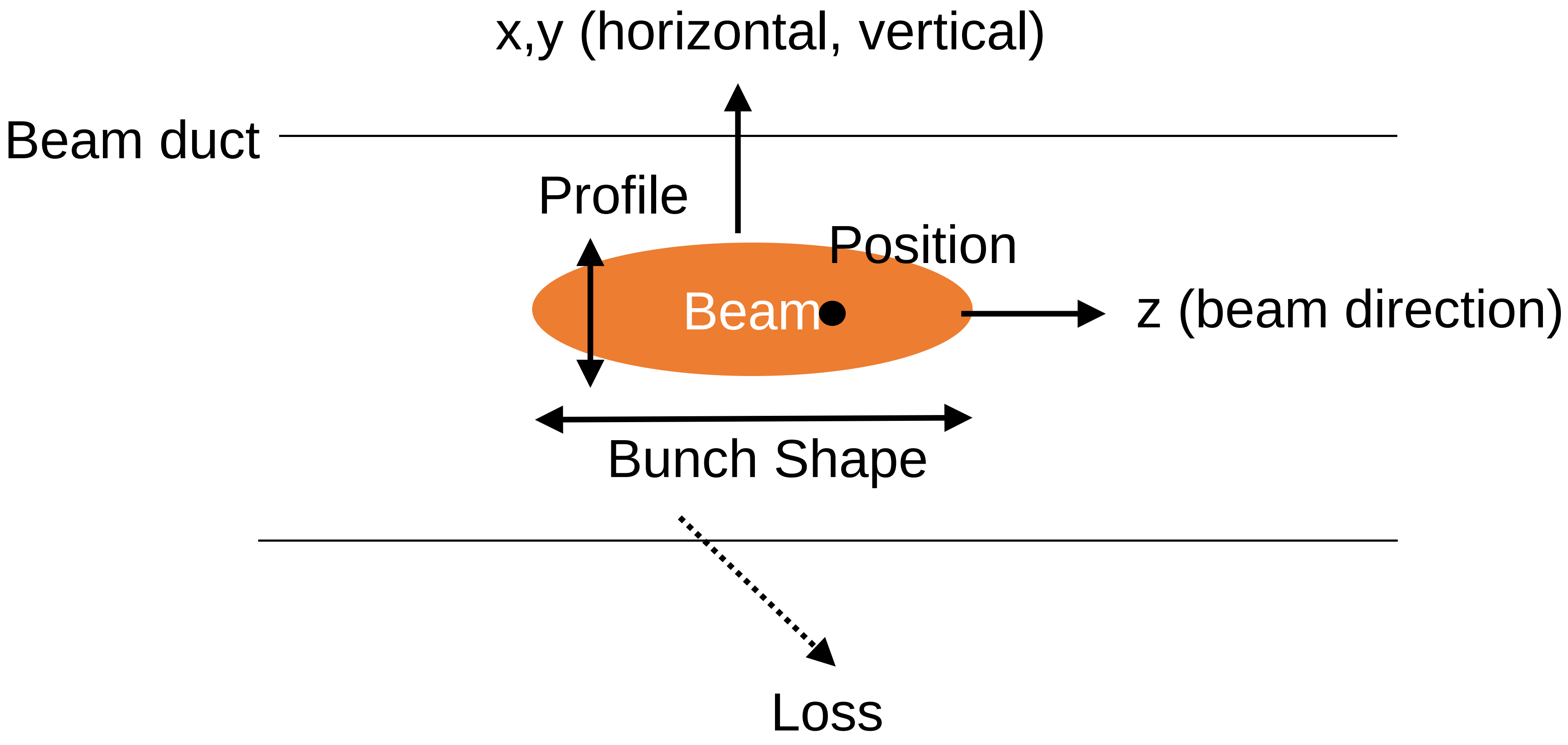
J-PARC



Tokai, Ibaraki
Kamioka
operation →
(goal) →
LINAC
16mA
(50mA)
3 GeV RCS
215 kW
(1MW)
ν detector
MLF
30 GeV MR
190kW
(750W)
Hadron hall


J-PARC
Main ring (MR)
Hadron
Rapid Cycling Synchrotron (RCS)
MLF
LINAC
Ion Source
Neutrino
http://j-parc.jp/Acc/ja/about.html

Monitors in J-PARC

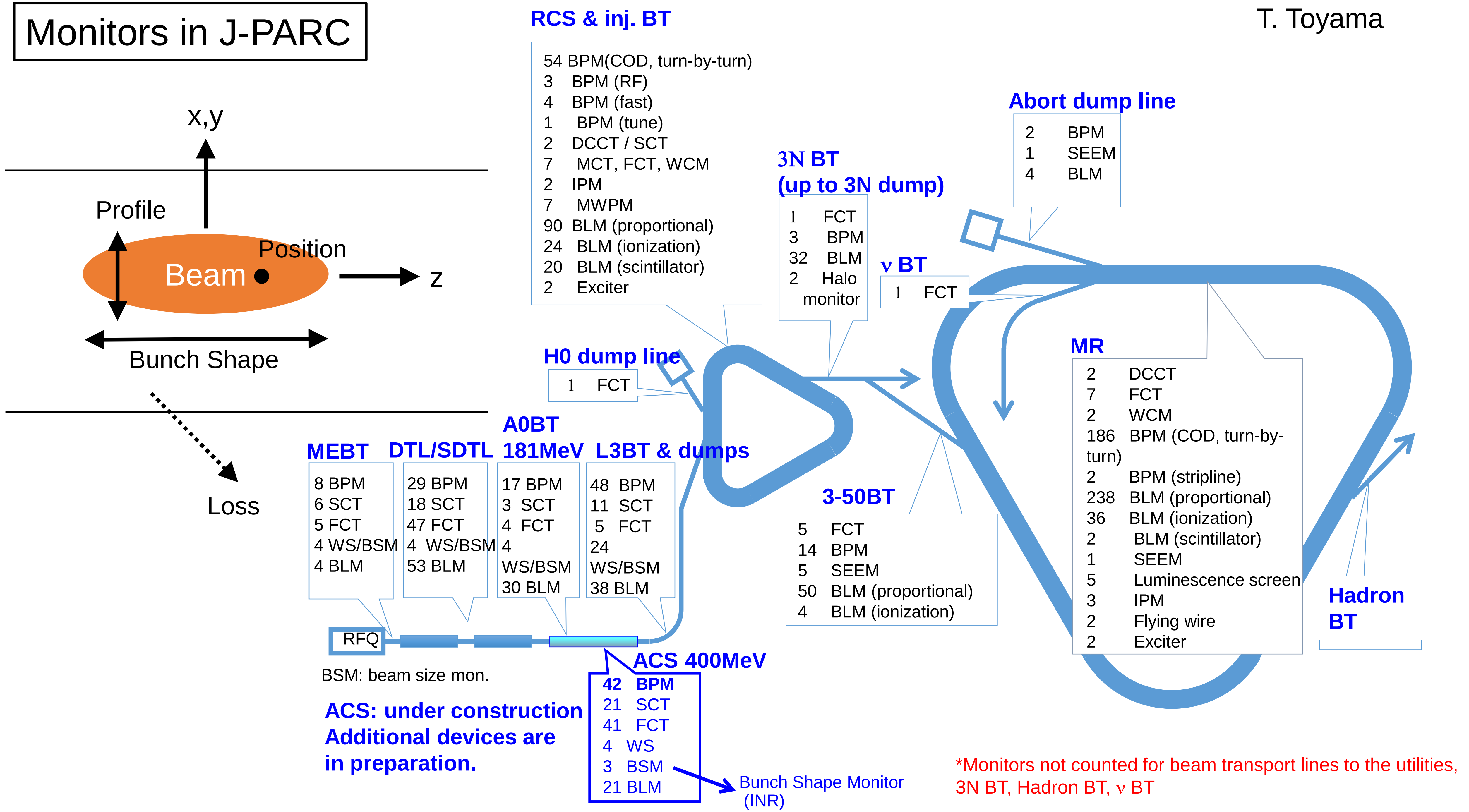


- Current
- Time varying information (Turn by Turn etc.)

etc.

Monitors in J-PARC

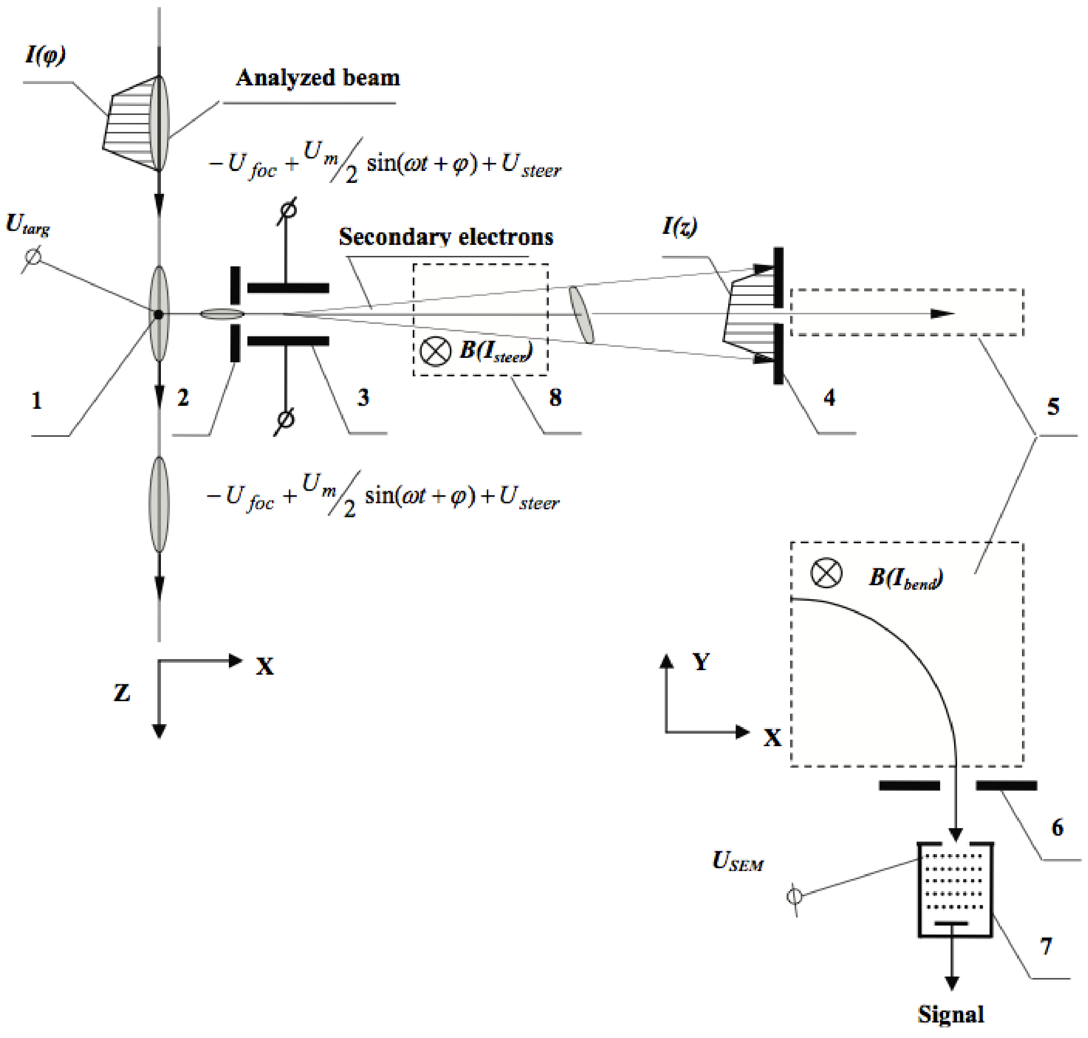
T. Toyama



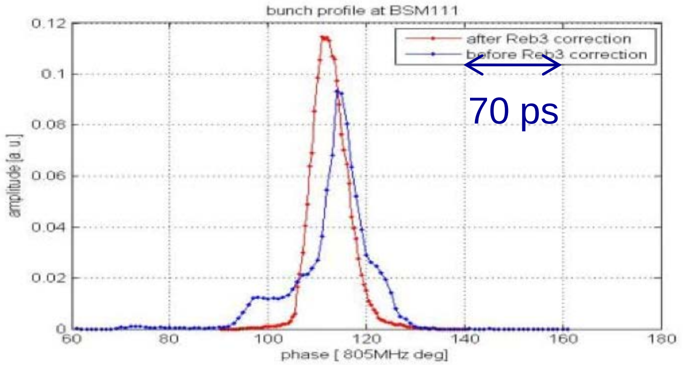
Bunch Shape Monitors (LINAC)

A. Miura et al.

- Developed by A.V.Feschenko, P.N. Ostroumov et al, INR, Moscow



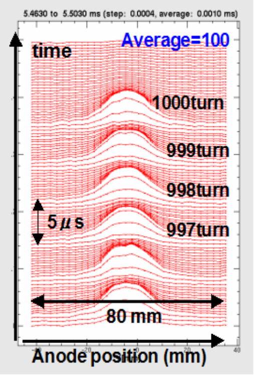
測定例 (A. V. Feschenko et al.,PAC07)

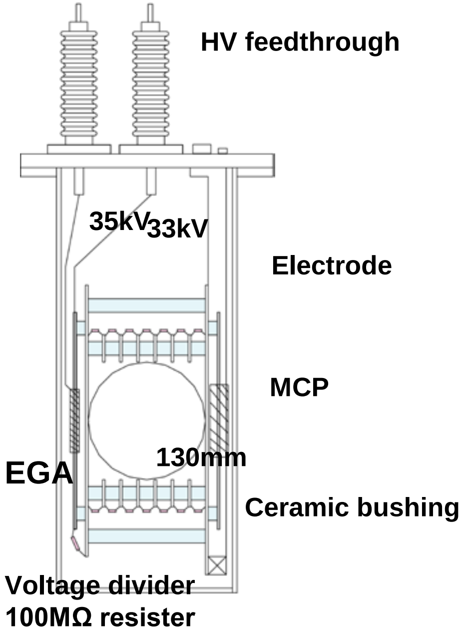


Profile Monitors

from T. Toyama

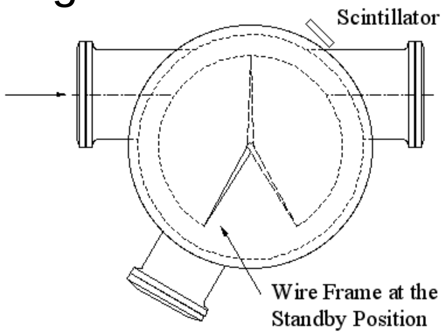
Residual gas Ionization Profile Monitor:
IPM
K. Satou et al.

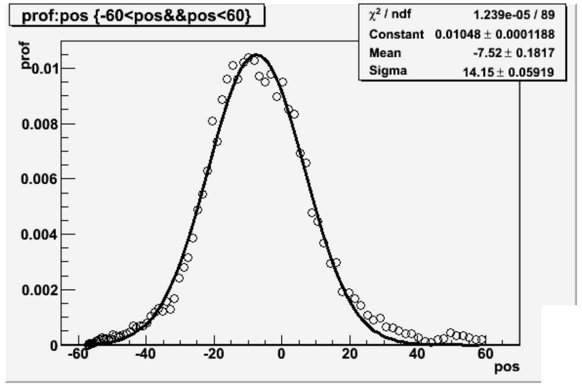




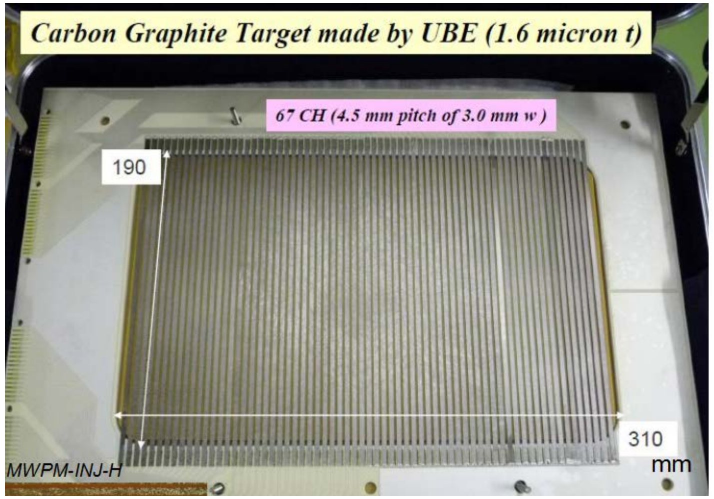
Cross section of V-IPM

Flying Wire Profile Monitor
S. Igarashi et al.

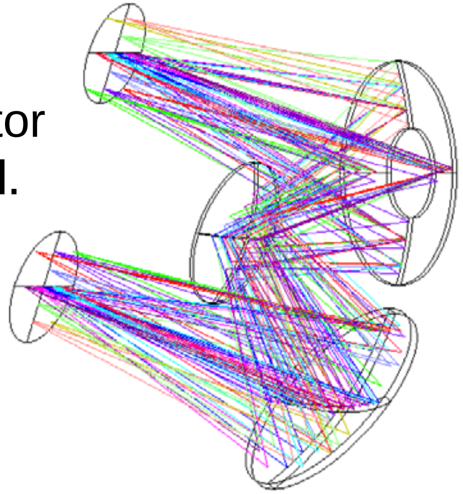




Multi Ribbon Beam Profile Monitor
Y. Hashimoto et al.



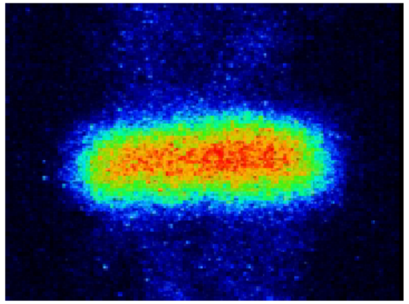
OTR Profile Monitor
Y. Hashimoto et al.

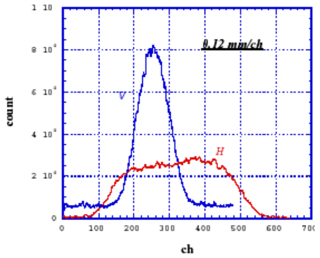


大広角オフナー・リレー・システム

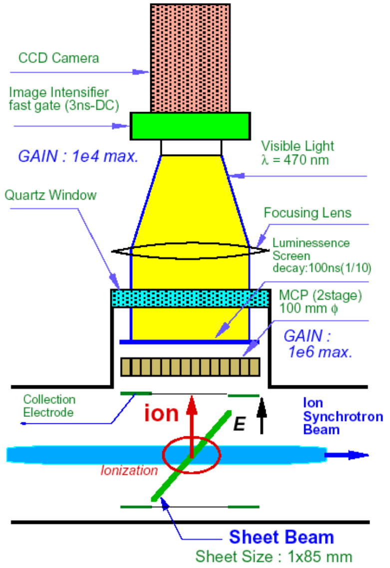
Gas-sheet
Beam Profile Monitor
Y. Hashimoto et al.

(a)





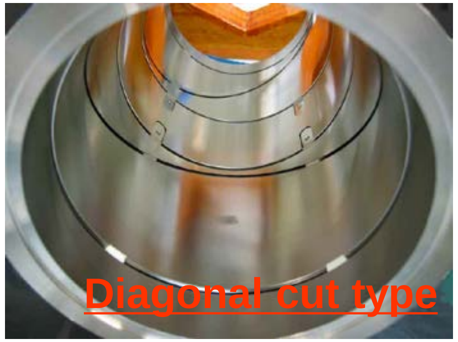
(b)

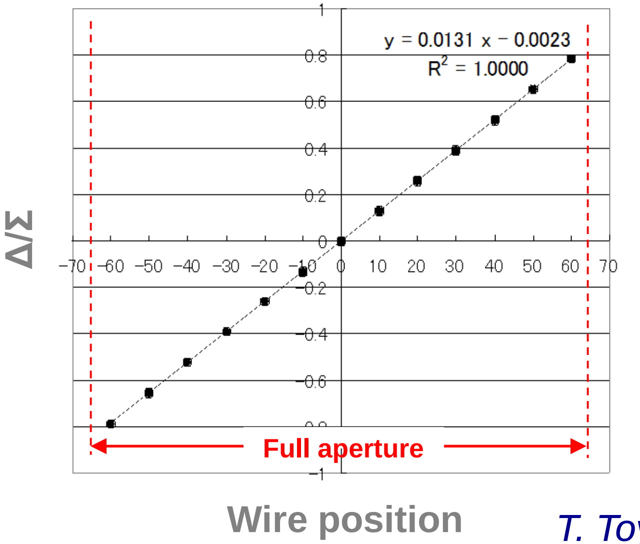


Beam Position Monitor (BPM)

- Same position as Q magnets (information of focus/defocus points)

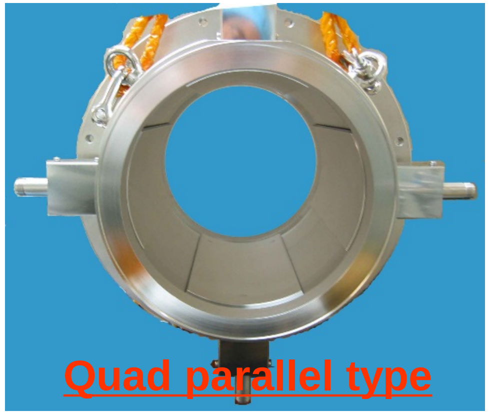
Diagonal cut electrode type (Main Ring)

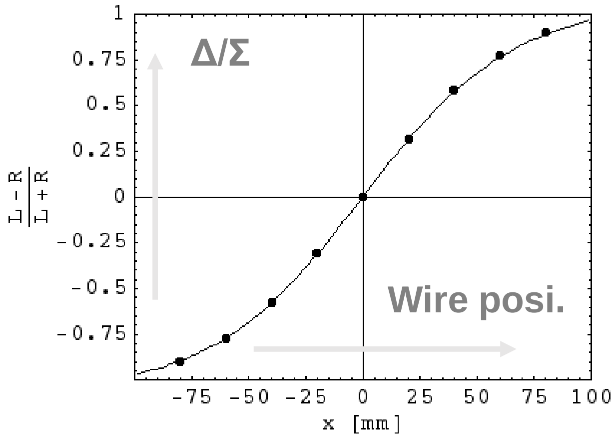




T. Toyama et al.

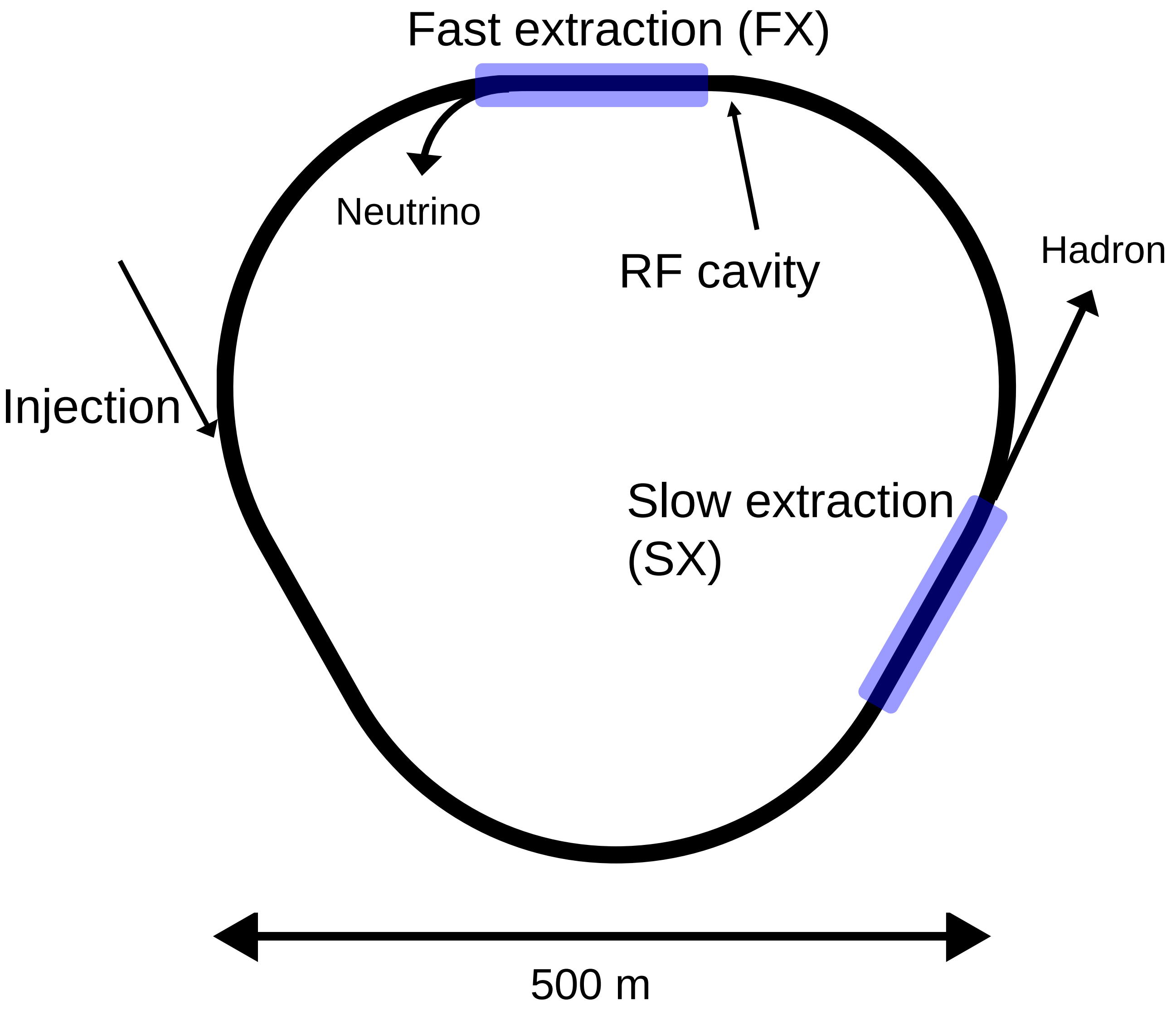
Parallel electrode type (Transport line)





D. Arakawa et al.

Main ring (MR)



Total length	1568 m
Energy	3-30 GeV
β	0.9715-0.9995
Lorentz γ	4.22-33.21
Harmonic	9
No. Bunches	8
Periods	5.38-5.23 μsec
RF freq.	1.67-1.72 MHz
Bunch length (time)	70～200 nsec
Bunch length (space)	20～60 m
Tune	FX: ν_x=22.40, ν_y=20.75 SX: ν_x=22.30, ν_y=20.78
No. of BPM	**186 (1 BPM/7-8 m)**

High intensity⇒reduction of beam loss

⇩

Stable beam orbit

Corrected COD

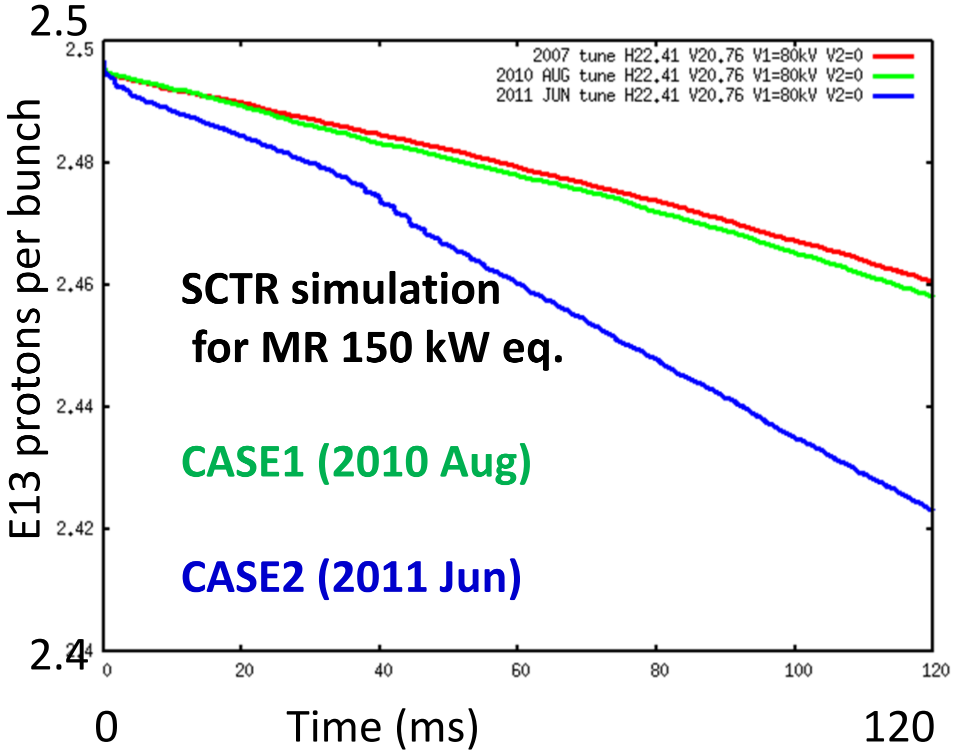
Y. Sato

- Alignment errors are inevitable

→ NEEDS COD correction

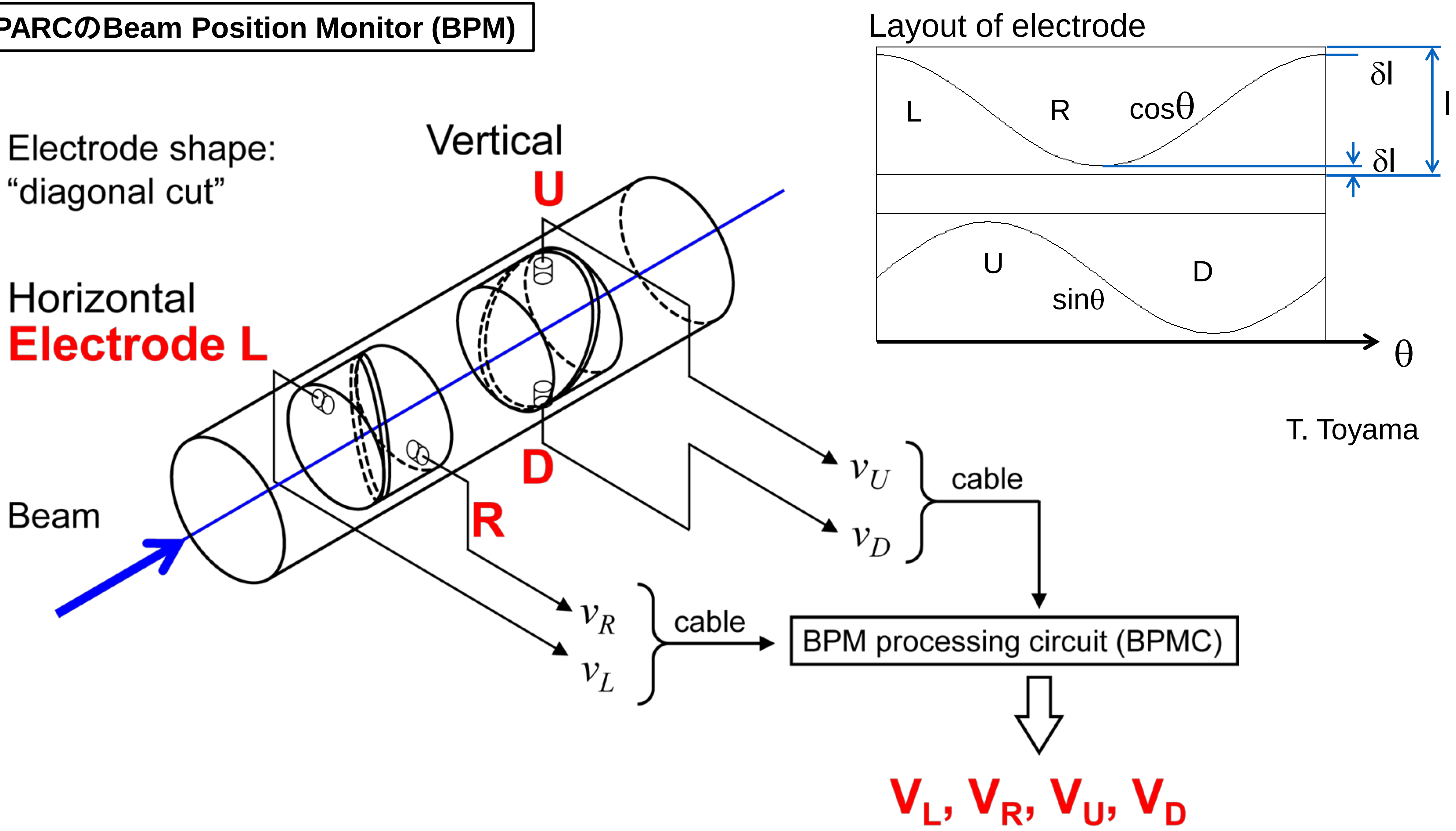
w USING steering magnets based on BPMs

- Accuracy of BPMs is a BIG KEY

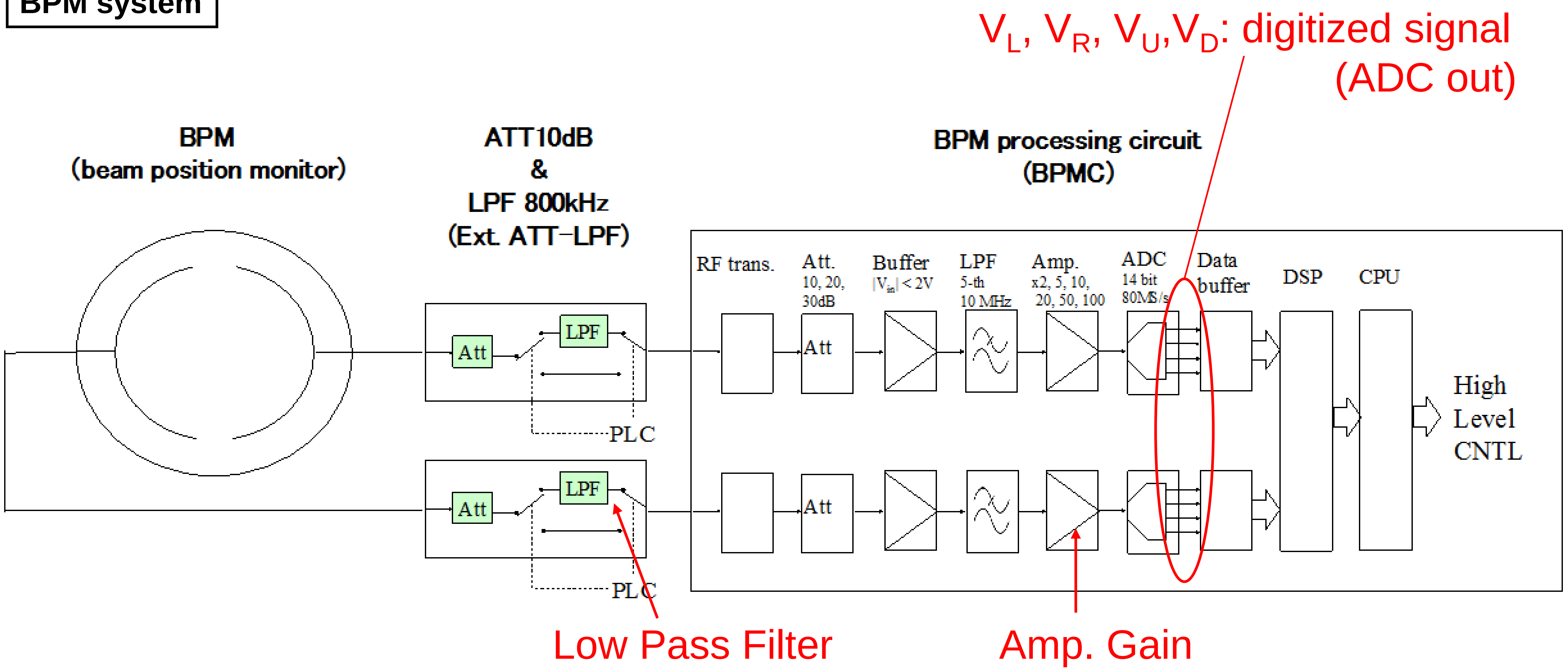


Model Alignment	Simulated (DX-QcX) rms	Simulated (DY-QcY) rms	Simulated beam loss in injection for MR 150 kW eq.
CASE1 (2010 Aug)	0.22 mm	0.19 mm	120 W (0.8%)
CASE2 (2011 Jun)	0.42 mm	0.37 mm	220 W (1.5%)

J-PARCのBeam Position Monitor (BPM)



BPM system



Different setup depending on beam intensity

T. Toyama

Position calculation

$$\begin{cases} V_L = \lambda g_L \left(1 + \dfrac{x}{a}\right) \\ V_R = \lambda g_R \left(1 - \dfrac{x}{a}\right) \\ V_U = \lambda g_U \left(1 + \dfrac{y}{a}\right) \\ V_D = \lambda g_D \left(1 - \dfrac{y}{a}\right) \end{cases}$$

$$\Rightarrow \quad x = \frac{V_L/g_L - V_R/g_R}{V_L/g_L + V_R/g_R} a, \qquad y = \frac{V_U/g_U - V_D/g_D}{V_U/g_U + V_D/g_D} a$$

g_L, g_R, g_U, g_D	Gains from electrode divided by Left gain (= g_L). g_L=1。
V_L, V_R, V_U, V_D	Signal strength from electrode L,R,U,D
λ	Beam intensity passing through BPM
x,y	Beam positions (horizontal, vertical)
a	Effective radius from BPM center

BPM alignment errors correction

↑

Beam Based Alignment (BBA) [2]

(1) Most effective method to correct BPM position error
→very effective but takes long term **(several days ～ 1 week)**

(2) Gain errors (signal transfer, electric circuit)

↓

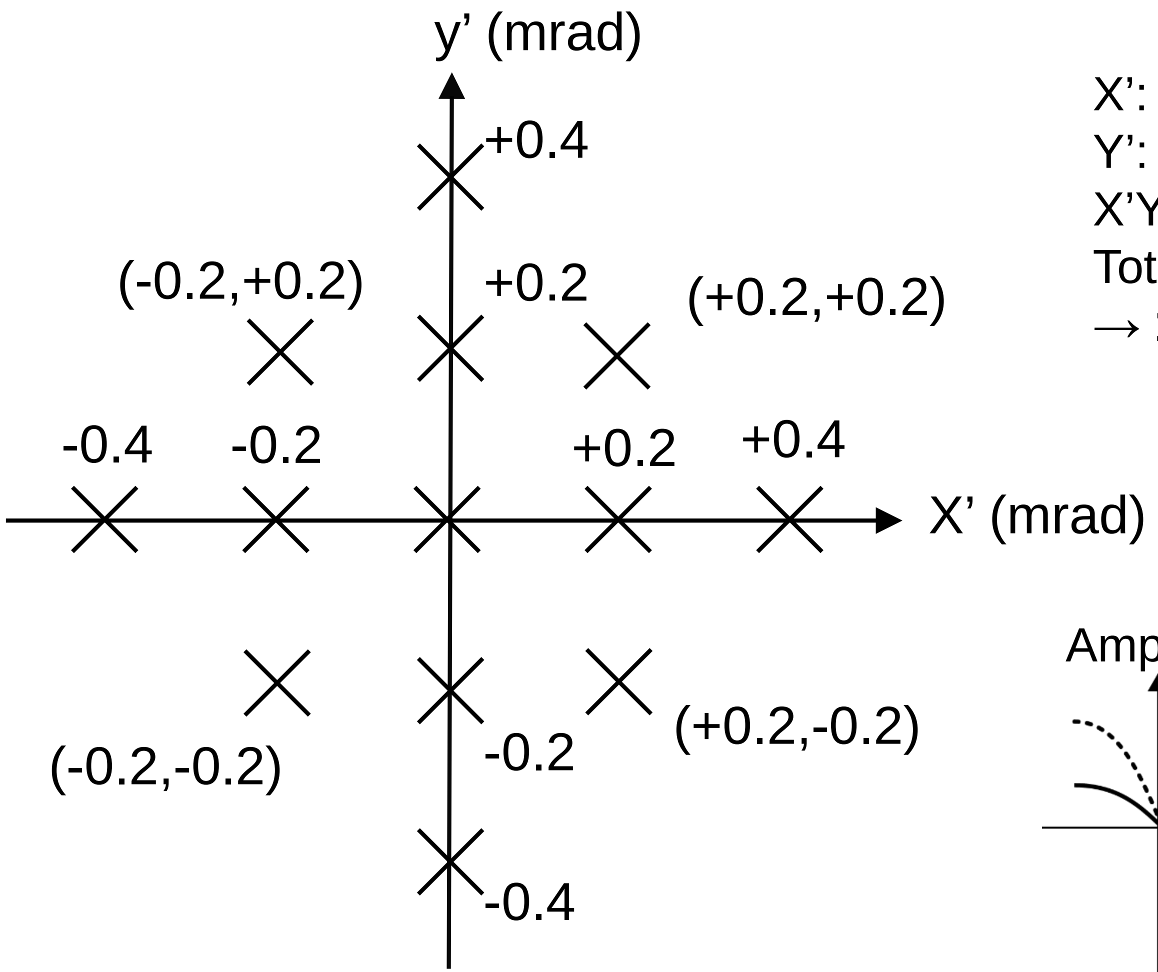
Beam Based Gain Calibration (BBGC) [3]

→data acquisition is easier than BBA (a few～ several hours)

[2] T. Toyama et al., PASJ meeting (2014).
[3] K. Satoh and M. Tejima, Proc. of PAC95, p. 2479 (1995).

BBGC (Beam Based Gain Calibration)

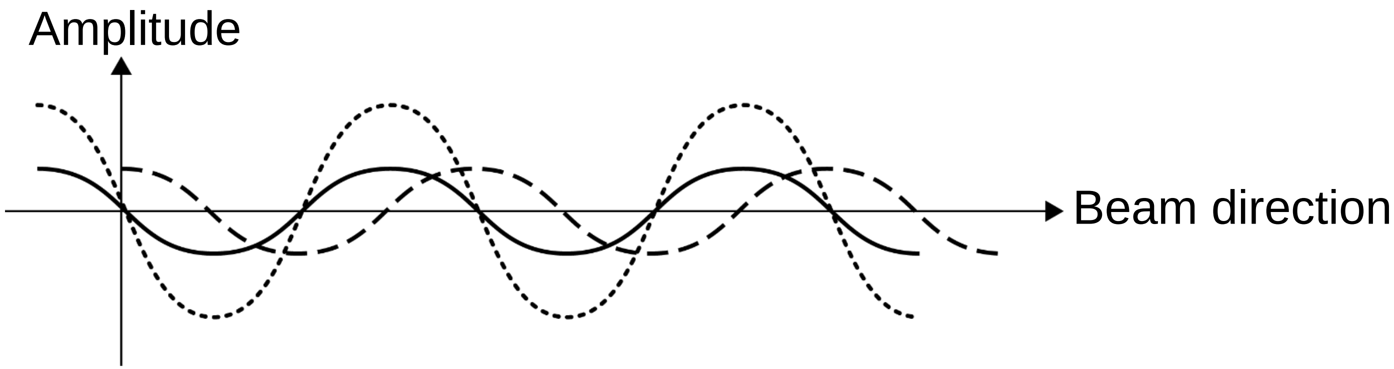
1) Kick the COD by steering magnet→larger amplitude
2) Orbit data with various amplitudes are acquired. Signal from each electrode varies depending on beam positions (below fig.).
3) Gains (g_L, g_R, g_U, g_D) are determined as reproducing the all signal strength from the electrodes.



X': 5 points
Y': 5 points
X'Y': 4 points
Total14 points
→ **14 points×10 shot×2 sets=280 data**

(x',y')=(ZSH001, ZSV216)
(ZSH210, ZSV209)

※2 phases pattern
gains of BPM at nodes are not well reproduced.



BBGC data analysis

$$\begin{cases} V_L = \lambda g_L\left(1+\frac{x}{a}\right) \\ V_R = \lambda g_R\left(1-\frac{x}{a}\right) \\ V_U = \lambda g_U\left(1+\frac{y}{a}\right) \\ V_D = \lambda g_D\left(1-\frac{y}{a}\right) \end{cases}$$

Remove x,y,a ⇒

$$\begin{cases} \lambda = \frac{1}{2}\left(\frac{V_L}{g_L}+\frac{V_R}{g_R}\right) \\ \lambda = \frac{1}{2}\left(\frac{V_U}{g_U}+\frac{V_D}{g_D}\right) \end{cases}$$

Remove λ ⇒

$$V_L = -\frac{1}{g_R}V_R + \frac{1}{g_U}V_U + \frac{1}{g_D}V_D \quad (g_L = 1)$$

Position
$$\begin{cases} x = \frac{V_L/g_L - V_R/g_R}{V_L/g_L + V_R/g_R}a \\ y = \frac{V_U/g_U - V_D/g_D}{V_U/g_U + V_D/g_D}a \end{cases}$$

Simplified: $-\frac{R}{g_R}+\frac{U}{g_U}+\frac{D}{g_D}=L$

- **m equations, m:number of data**

$$\begin{pmatrix} -R_1 & U_1 & D_1 \\ \vdots & \vdots & \vdots \\ -R_m & U_m & D_m \end{pmatrix} \begin{pmatrix} 1/g_R \\ 1/g_U \\ 1/g_D \end{pmatrix} = \begin{pmatrix} L_1 \\ \vdots \\ L_m \end{pmatrix}$$

A **x** **b**

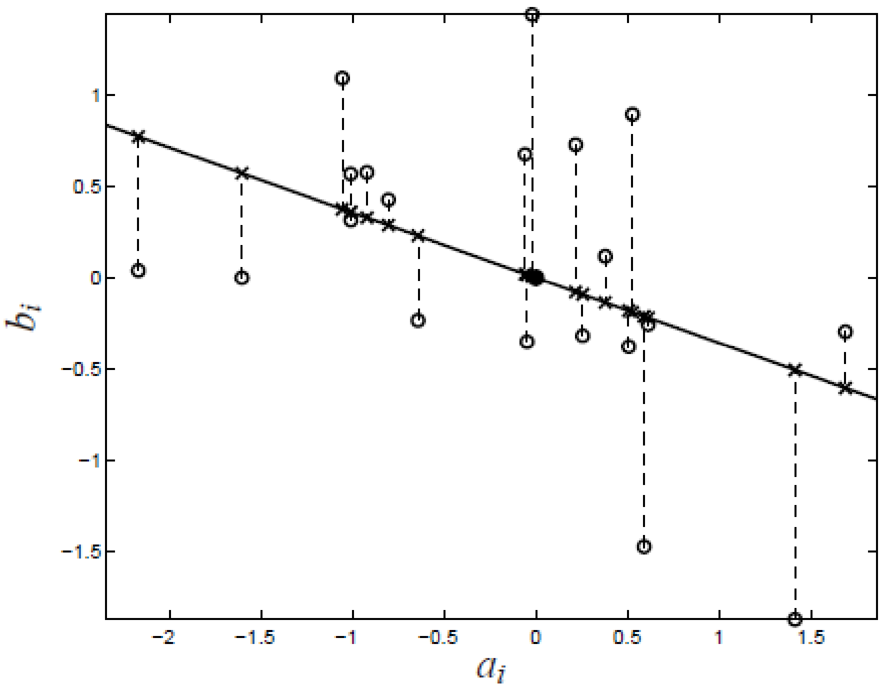
Calculation of gains

⇓

Solve the A·x=b equations

Method

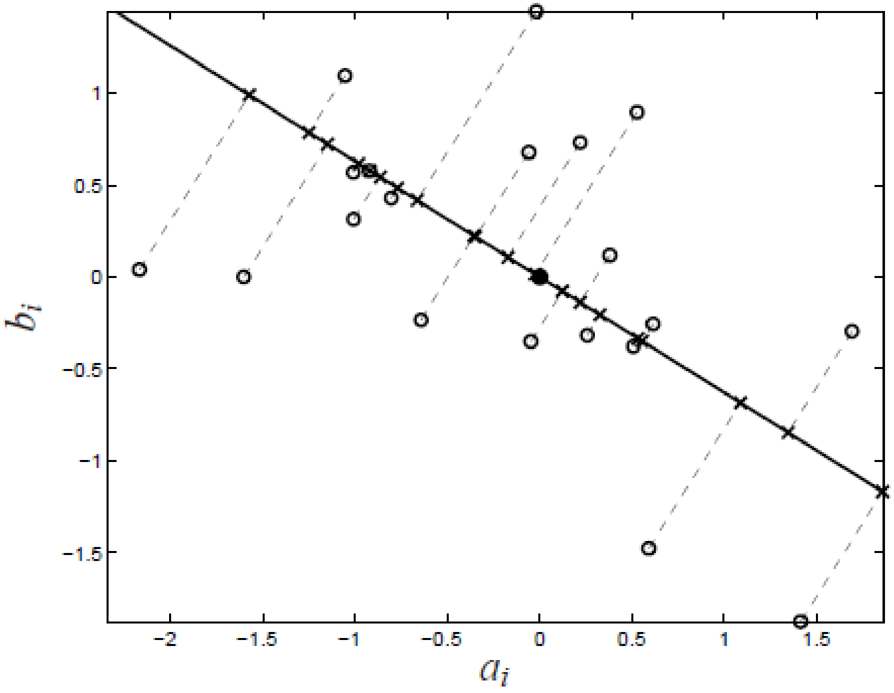
(1) Least Square Fitting (LS)



Minimize: residual ΔR

$$\Delta \mathrm{R} = \sum_{j=1}^{m} \left(-\frac{R_j}{g_R} + \frac{U_j}{g_U} + \frac{D_j}{g_D} - L_j \right)^2$$

(2) Total Least Square Fitting (TLS)



Minimize: total distance ΔD

$$\Delta D = \frac{1}{\|\boldsymbol{G}_{\perp}\|^2} \sum_{j=1}^{m} \left(-\frac{R_j}{g_R} + \frac{U_j}{g_U} + \frac{D_j}{g_D} - L_j \right)^2$$

$$\boldsymbol{G}_{\perp} = \left(-1, -\frac{1}{g_R}, \frac{1}{g_U}, \frac{1}{g_D} \right)$$

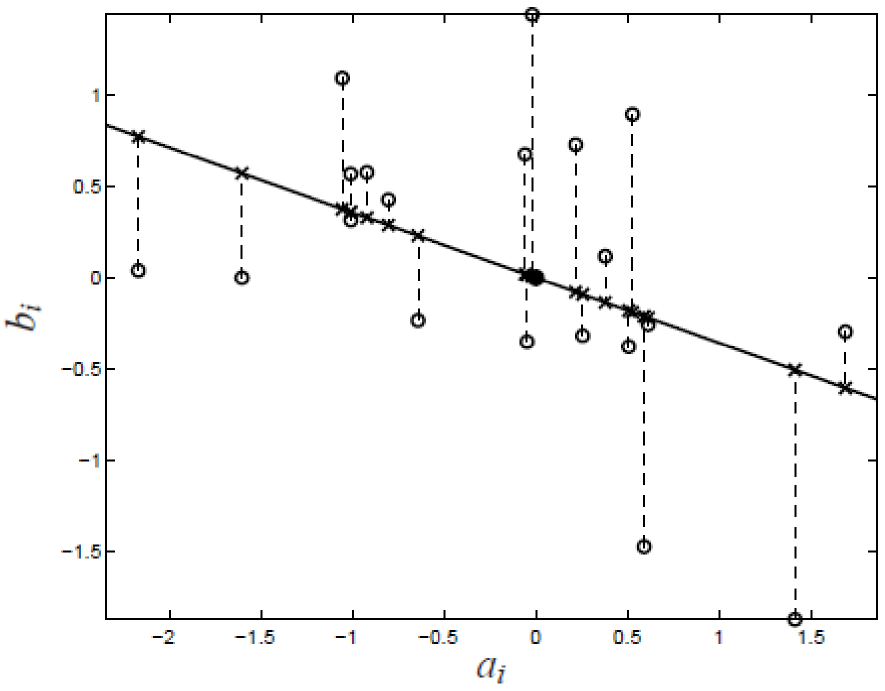
$\boldsymbol{G}_{\perp}$: plane equation in L,R,U,D:

$$-L - \frac{R}{g_R} + \frac{U}{g_U} + \frac{D}{g_D} = 0$$

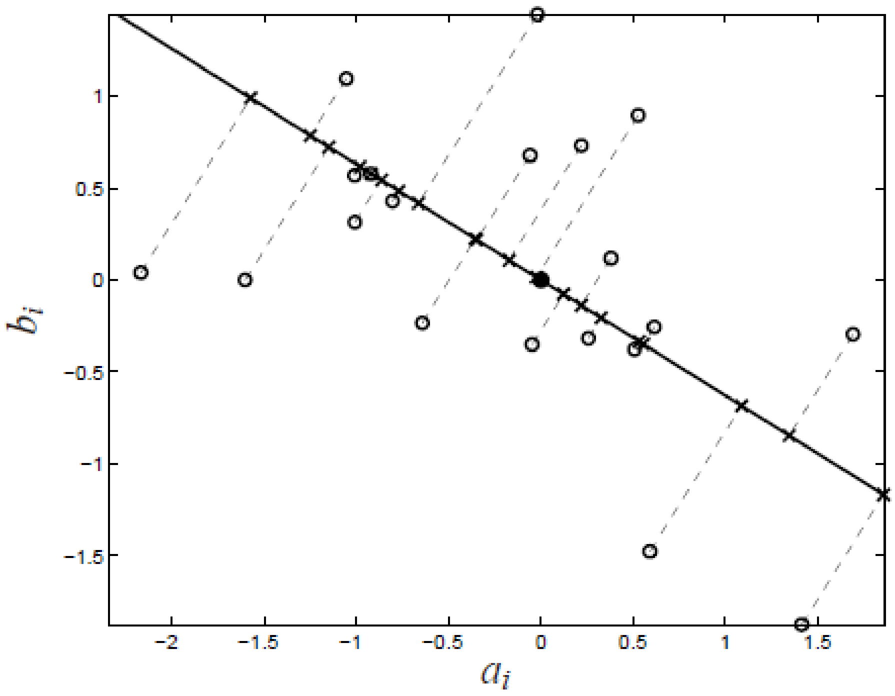
vector perpendicular to the plane

Method

(1) Least Square Fitting (LS)



(2) Total Least Square Fitting (TLS)



Calculation procedure

$$[A]\boldsymbol{x} = \boldsymbol{b}$$

$$[A^T][A]\boldsymbol{x} = [A^T]\boldsymbol{b}$$

$$[A^TA]^{-1}[A^T][A]\boldsymbol{x} = [A^TA]^{-1}[A^T]\boldsymbol{b}$$

$$\therefore \boldsymbol{x} = [A^TA]^{-1}[A^T]\boldsymbol{b}$$

$$[A]\boldsymbol{x} = \boldsymbol{b}$$

$$\left[[A^T][A] - \lambda \boldsymbol{I}\right]\boldsymbol{x} = [A^T]\boldsymbol{b}$$

$$\left[[A^T][A] - \lambda \boldsymbol{I}\right]^{-1}\left[[A^T][A] - \lambda \boldsymbol{I}\right]\boldsymbol{x} = \left[[A^T][A] - \lambda \boldsymbol{I}\right]^{-1}[A^T]\boldsymbol{b}$$

$$\therefore \boldsymbol{x} = \left[[A^T][A] - \lambda \boldsymbol{I}\right]^{-1}[A^T]\boldsymbol{b}$$

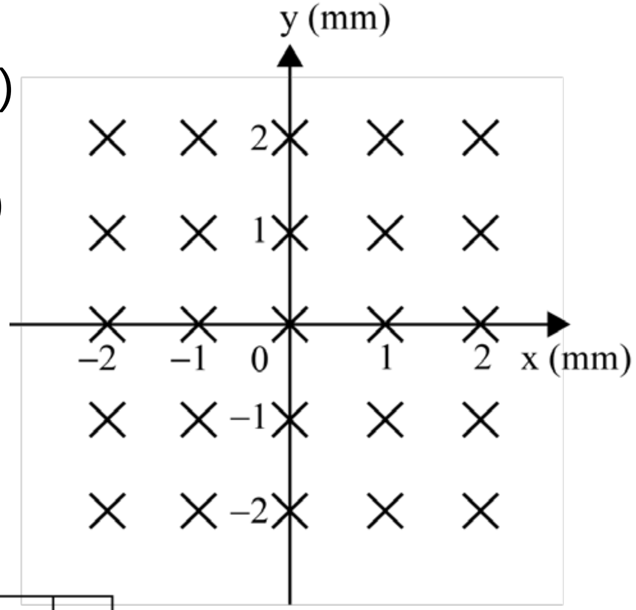
λ: unknown const.

$\boldsymbol{I}$: Unit matrix

Simulation

①: Preparation of Gains $V_L = \lambda g_L \left(1 + \frac{x}{a}\right)$ $(g_L, g_R, g_U, g_D) = (1.00, 1.01, 1.005, 0.975)$

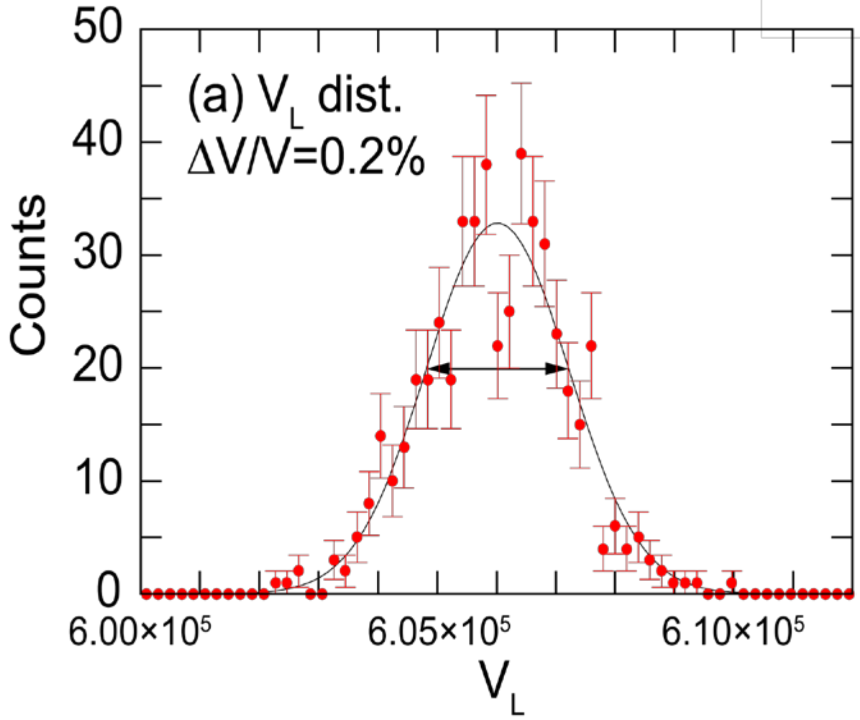
②: Determine positions $V_L = \lambda g_L \left(1 + \frac{x}{a}\right)$ $-2 \le x \le 2$, $-2 \le y \le 2$, 25 points (right fig.)



③: Determine the signal for each position and gain $V_L = \lambda g_L \left(1 + \frac{x}{a}\right)$

④: Noise generation for V assuming ΔV/V = 0.2% with Gaussian distribution

⑤: 500 data points are generated for 1 position

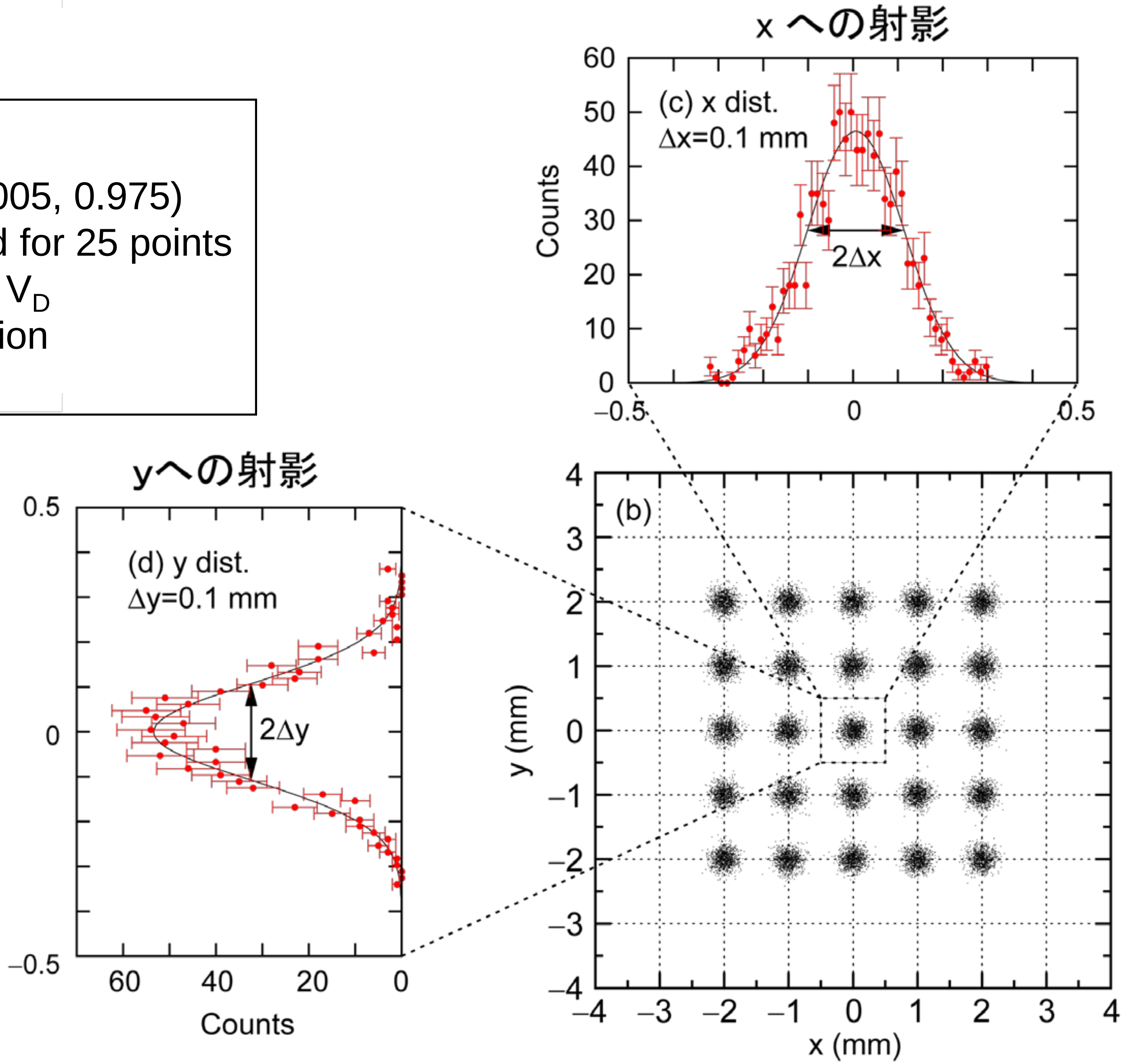


λ: Coef. of beam int.
a: calibrated value by offline

Simulation

Conditions:

- True gains:
  $(g_L, g_R, g_U, g_D) = (1.00, 1.01, 1.005, 0.975)$
- $-2 \le x \le 2$, $-2 \le y \le 2$, generated for 25 points
- Noise generation for V_L, V_R, V_U, V_D
  $\Delta V/V = 0.2\%$ Gaussian distribution
- 500 points per 1 position



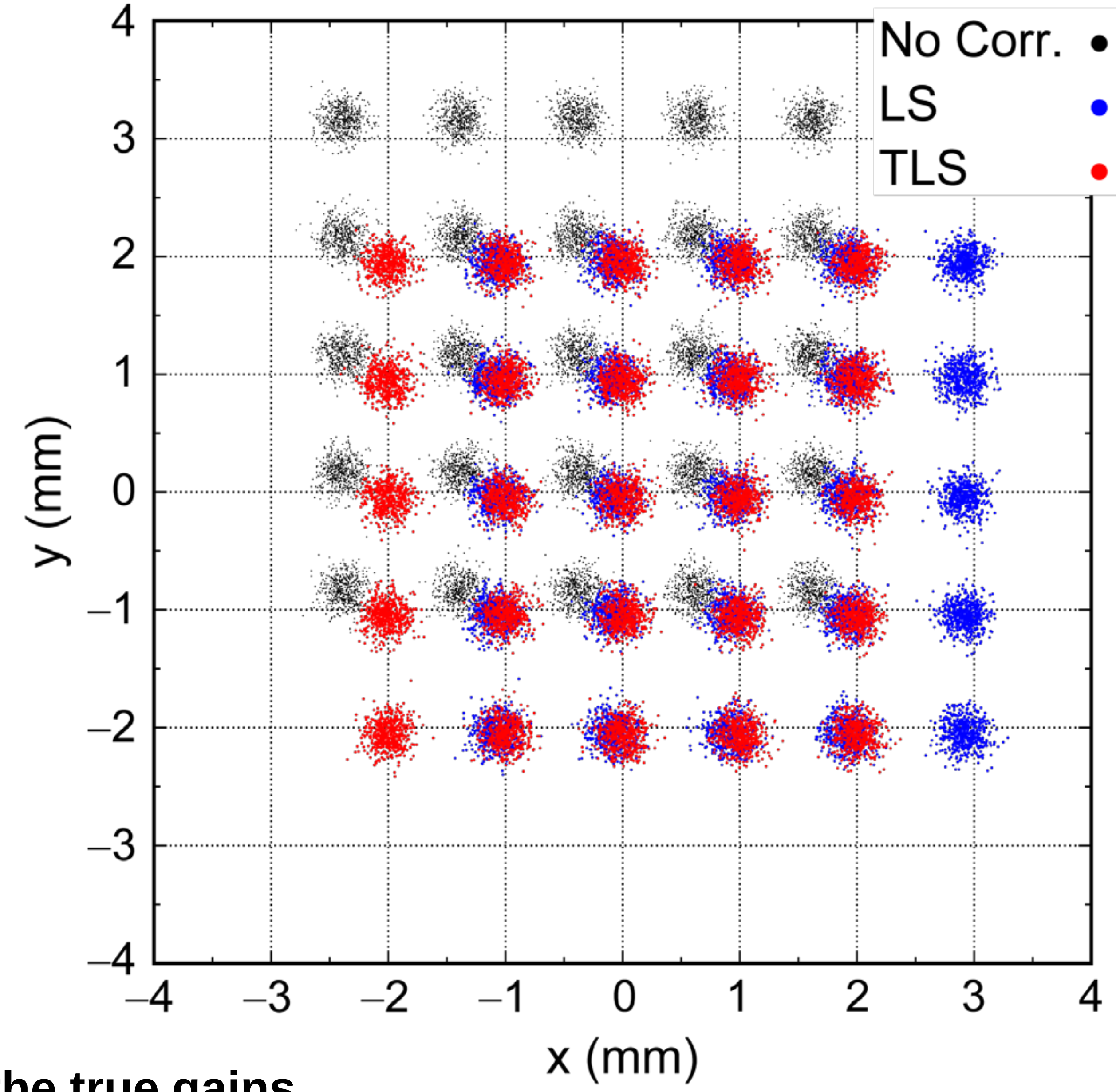
Fitting results

	g_R	g_U	g_D
True	1.010	1.005	0.975
LS	1.034	1.015	0.988
TLS	1.012	1.005	0.977

LS: Least Square Fitting
TLS: Total Least Square Fitting

# of data: m=25×500=12500

$$\begin{pmatrix} -R_1 & U_1 & D_1 \\ \vdots & \vdots & \vdots \\ -R_m & U_m & D_m \end{pmatrix} \begin{pmatrix} 1/g_R \\ 1/g_U \\ 1/g_D \end{pmatrix} = \begin{pmatrix} L_1 \\ \vdots \\ L_m \end{pmatrix}$$

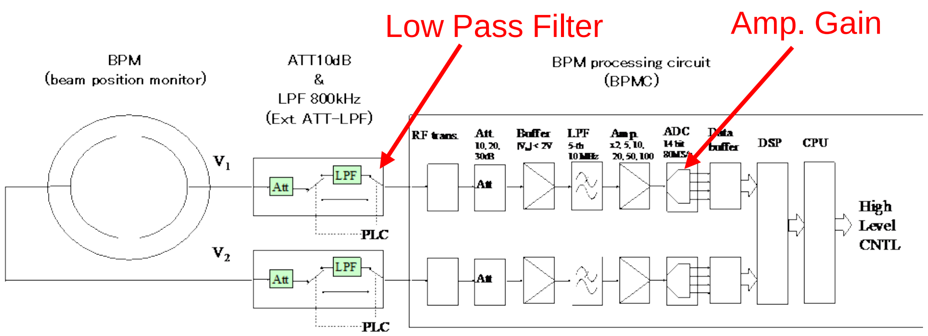


TLS method can adequately reproduce the true gains.

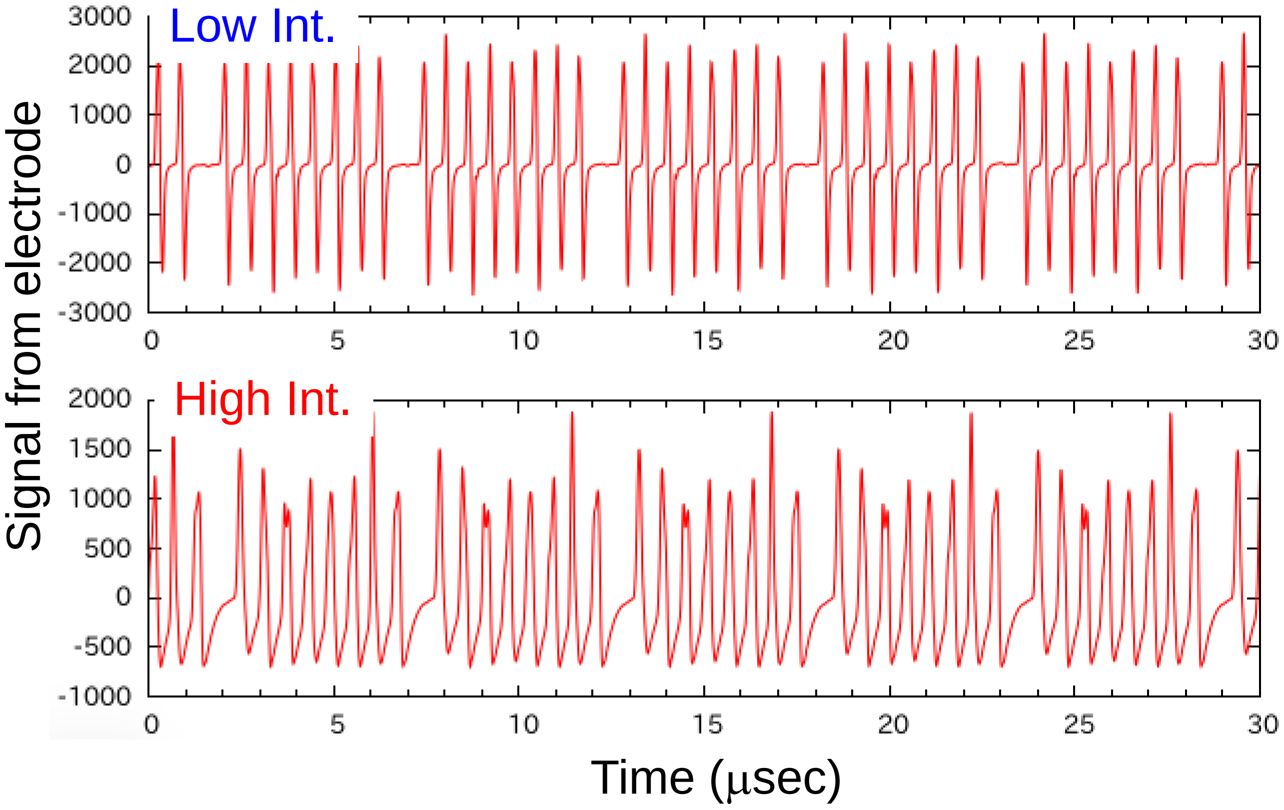
Analysis (Beam data)

- Gains vary depending on the settings of the circuit

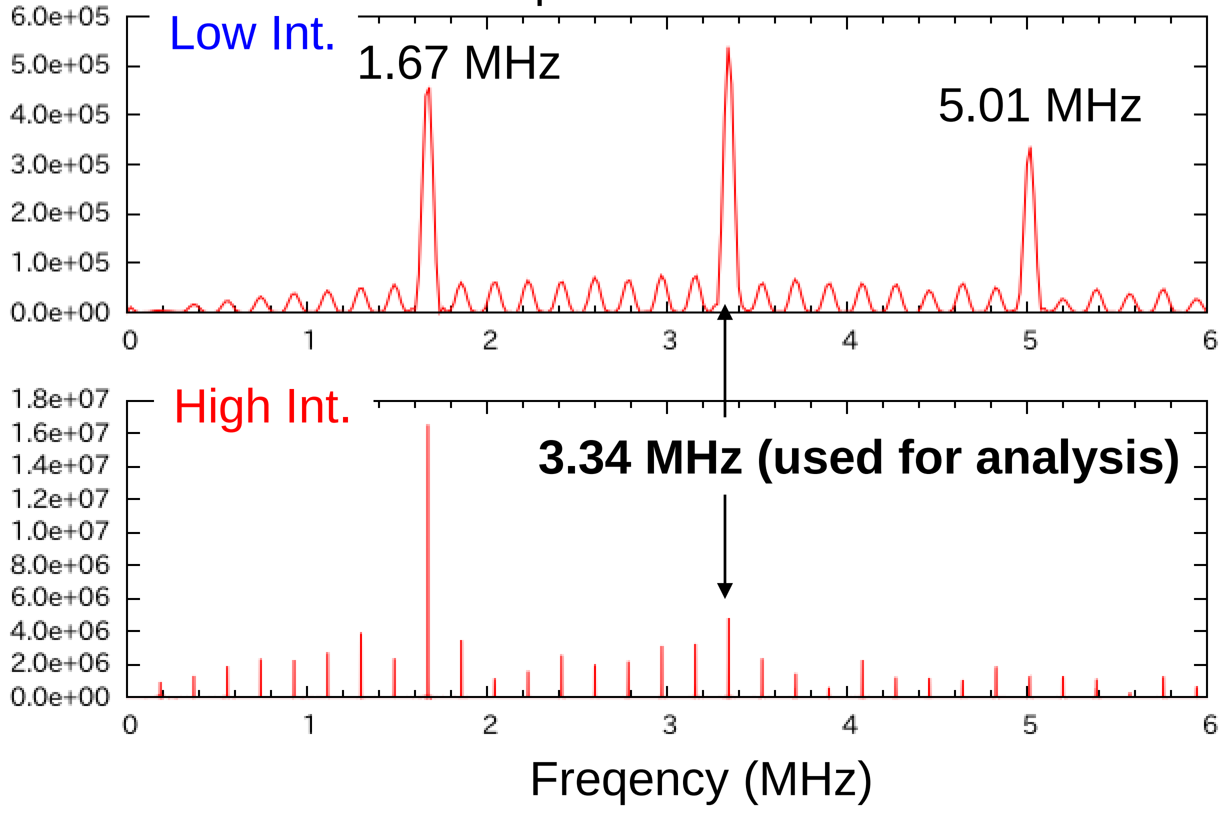
	Proton/8-bunch	Amp. gain	Low Pass Filter
Low Int.	2×10^{13}	×5	OFF
High Int.	1×10^{14}	×2	ON



Waveform from each electrode

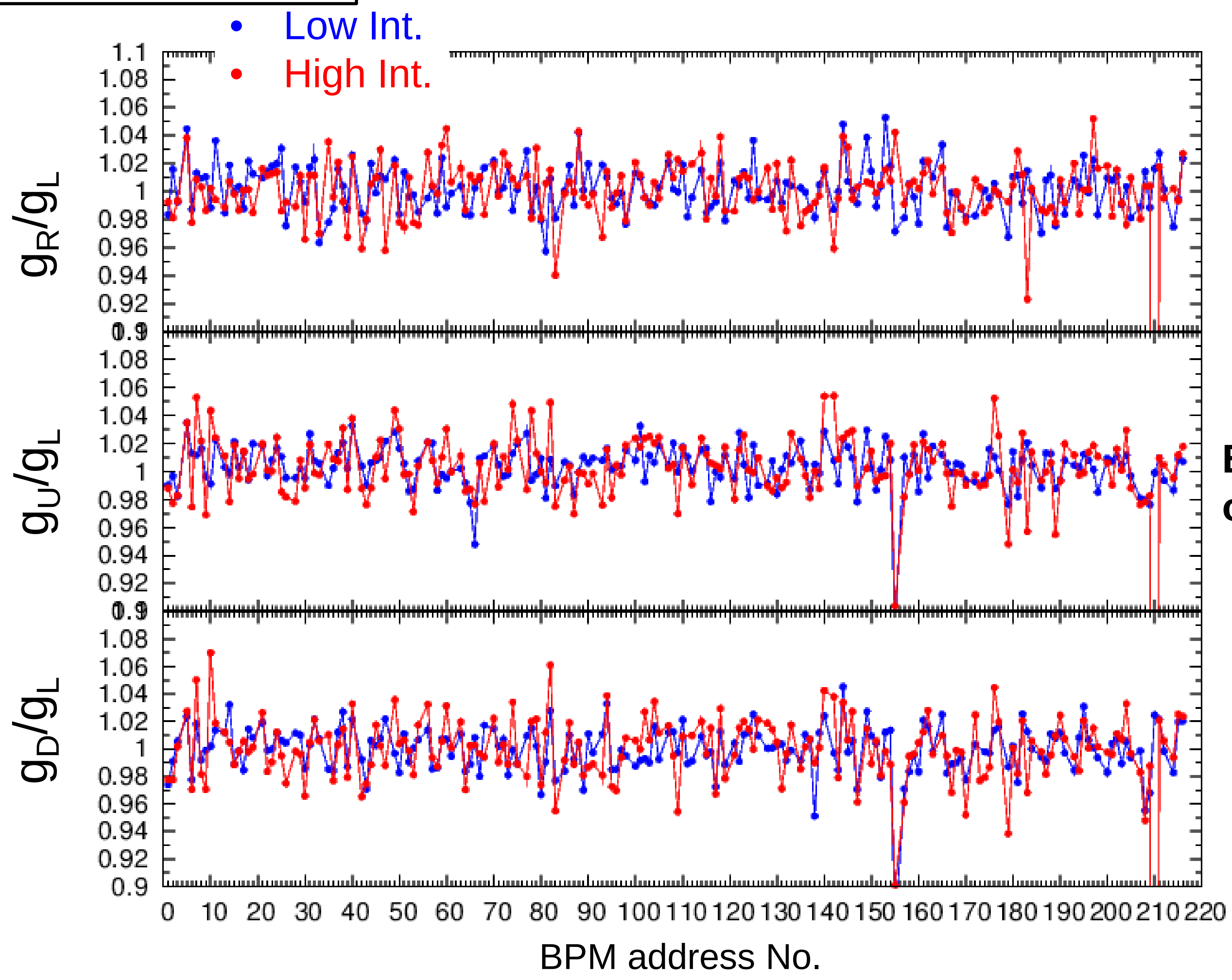


FFT spectra of waveform



Gains are calculated for 3.34 MHz peak (signal strength from L,R,U,D)

Results of gain calculation



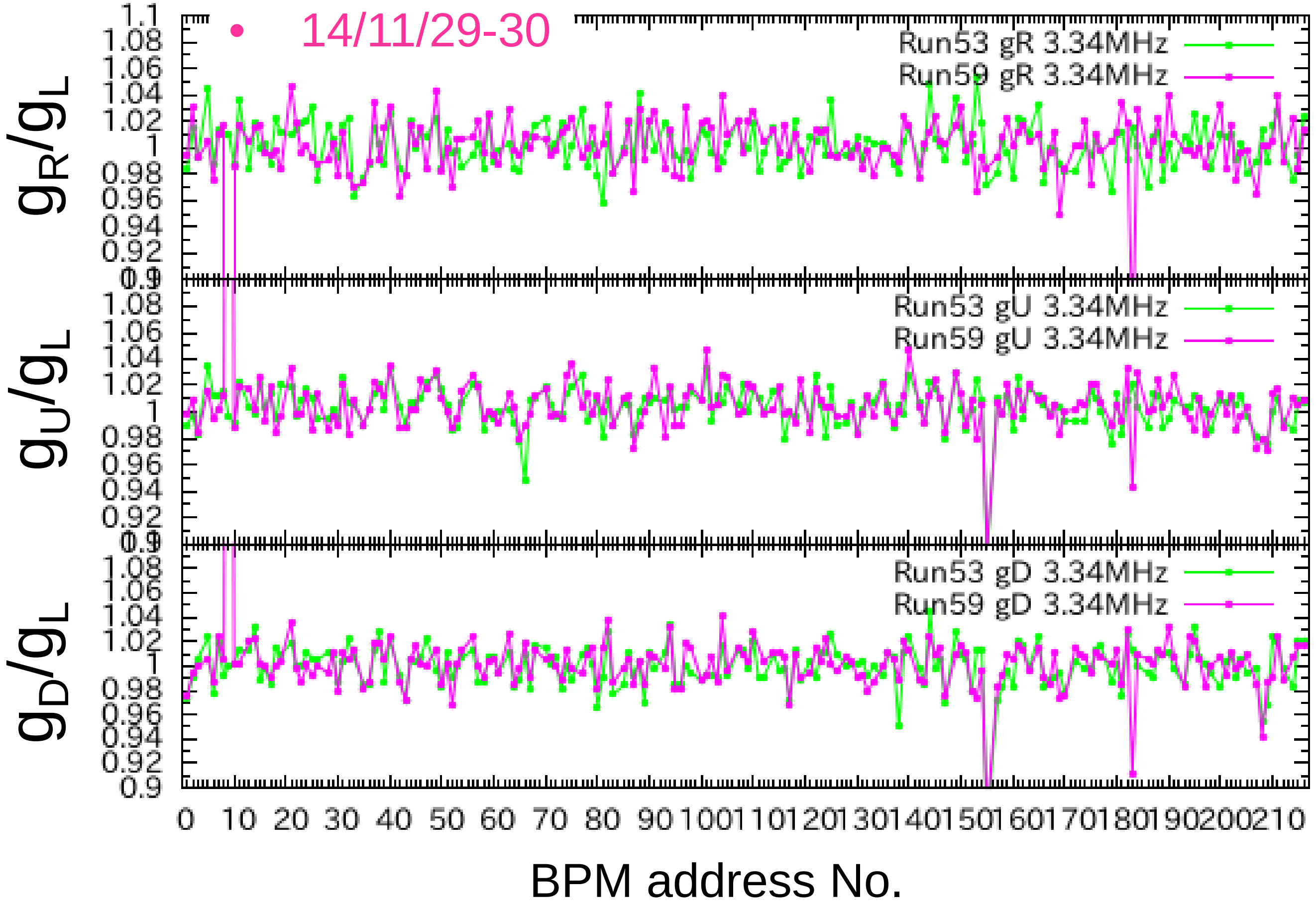
Maximally a few-several % difference

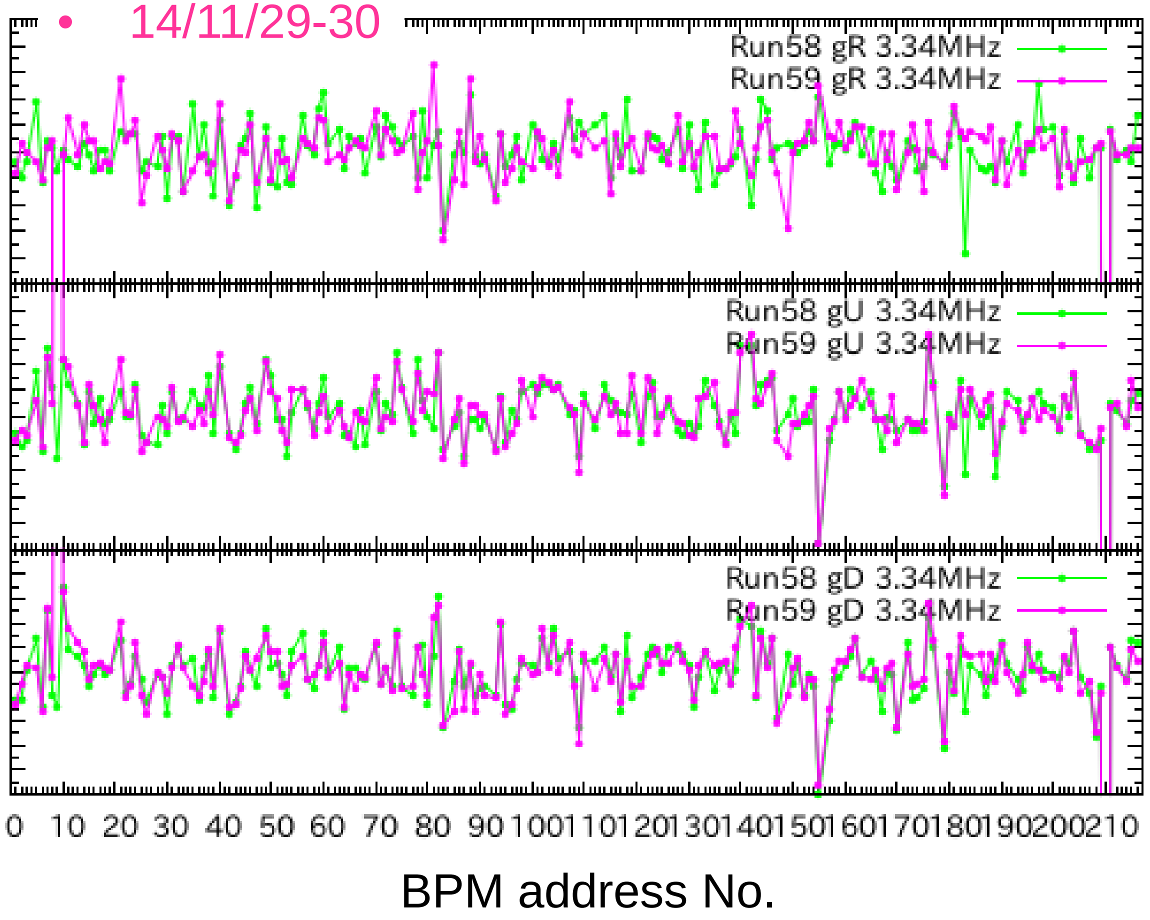
BBGC is needed depending on beam intensity

Difference of gains by derived by different Runs

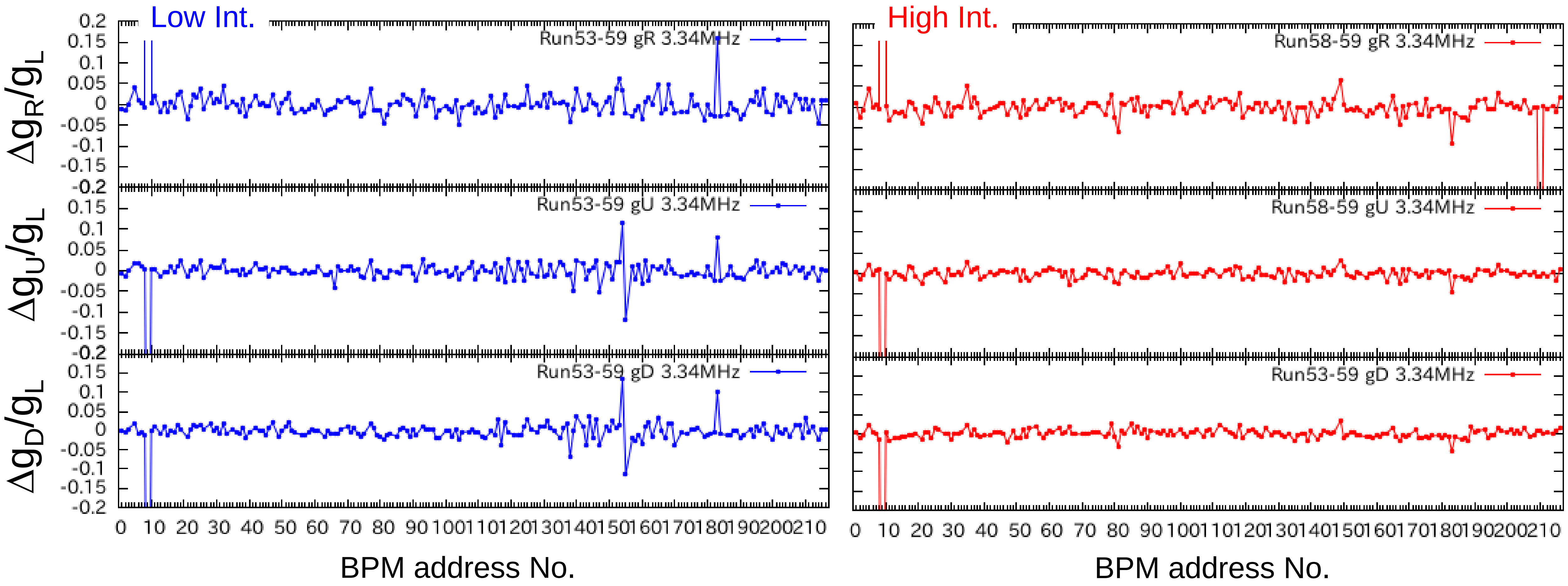
Low Int.
- 14/04/01
- 14/11/29-30

High Int.
- 14/11/05-06
- 14/11/29-30



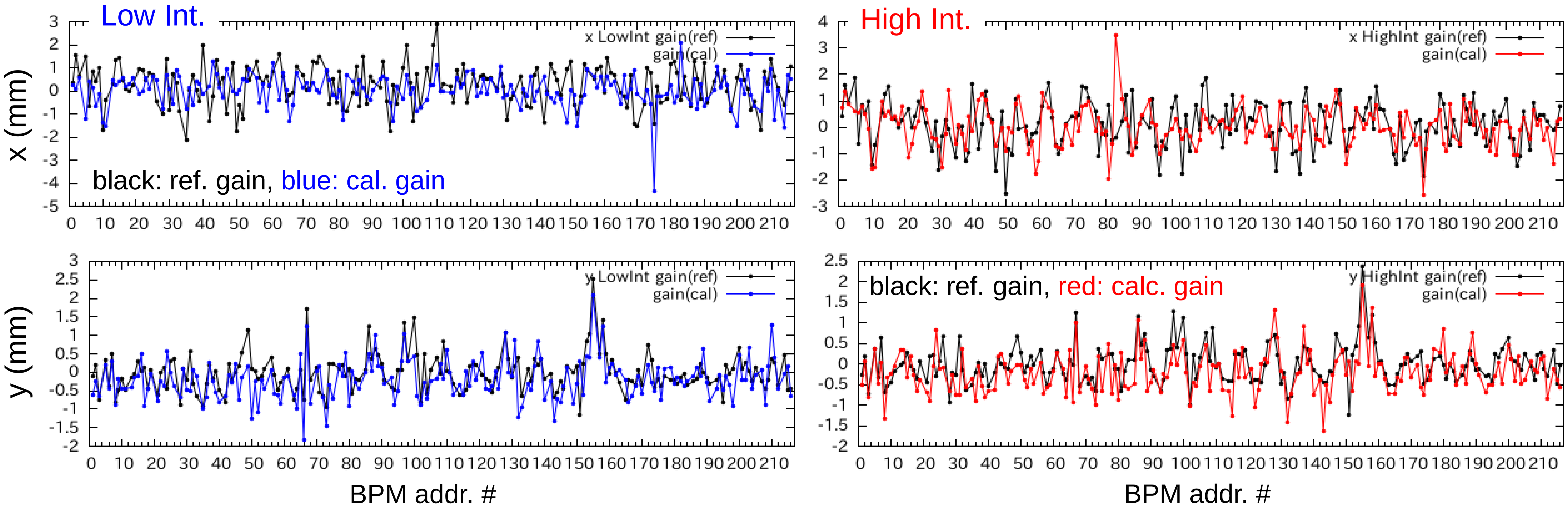


Difference of gains by derived by different Runs



Evaluation of the results

- Evaluated by Root Mean Square (RMS)= $\sqrt{\sum x_i^2 / n}$ of COD position for Low and High beam intensities



	Low Int.		High Int.	
	RMS x	RMS y	RMS x	RMS y
Ref. gain	0.896	0.506	0.871	0.460
Cal. gain	0.773	0.555	0.779	0.549

Summary (mainly Beam Based Gain Calibration**)**

- 186 BPMs are used in J-PARC MR for COD correction
- Required accuracy ～ a few 100 μm
  Correction of alignment errors of BPMs is necessary
- BPM gain has individuality by signal transfer or electric circuit.
  Beam Based Gain Calibration (BBGC) is effective method to correct position error along with Beam Based Alignment (BBA)
- Gains vary with the setting of electric circuit depending on beam intensity.
  BBGC has been done for “Low” and “High” beam intensity.
  RMS of COD was improved for x position
  while RMS of y became worse→under investigation (real difference in gains or some errors?)

◆ Establishment of BBGC for various beam intensities and will be applied for corrections of position errors.