Design and Offline tests of Button BPM for an IR-FEL project at NSRL

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1. Introduction of the IR-FEL project

Machine Layout

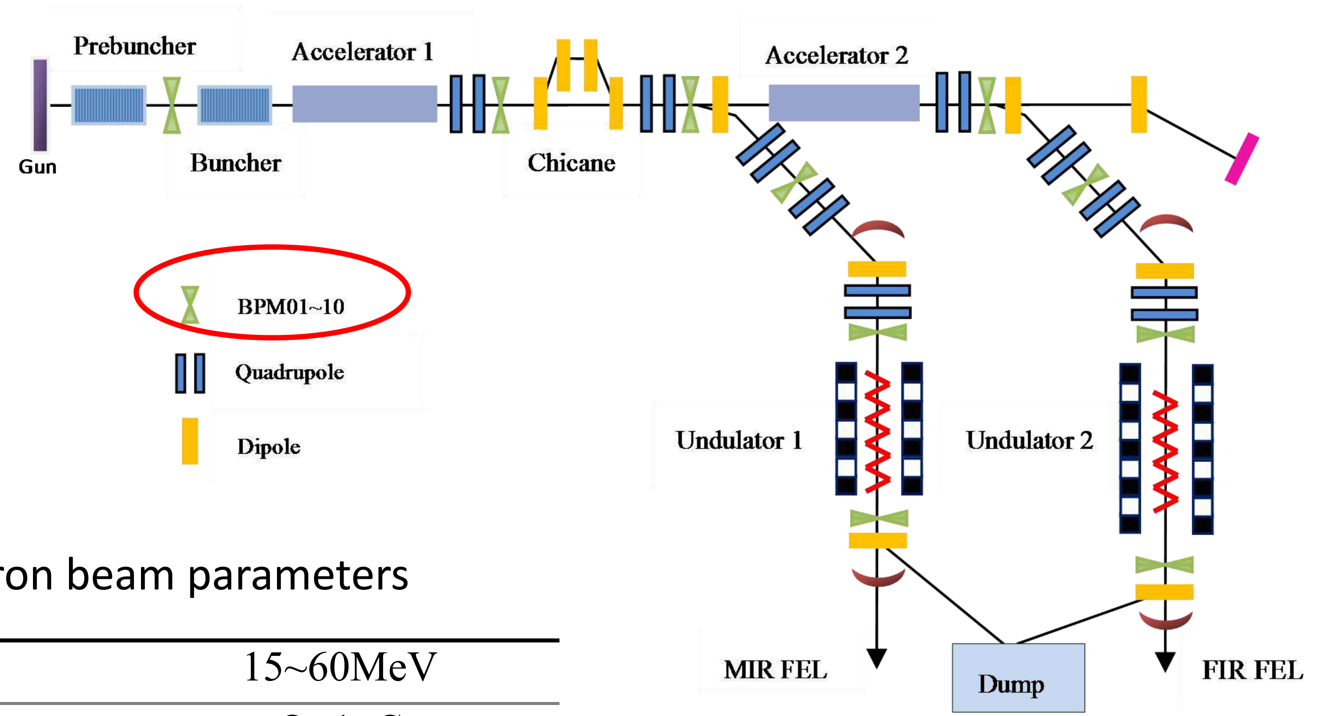


Table 1: Electron beam parameters

Beam energy	15~60MeV
Bunch charge	Q=1nC
Bunch length, rms	σ=2~5ps
Bunch repetition rate	59.5,119,238,476MHz
Macro pulse length	Max:10μs
Macro pulse repetition rate	20Hz

Compact :

Room area: $12*24m^2$

2. Design of Button BPM

- Requirements:

1. Low cost and Compact
2. Resolution<50μm for different repetition rates

Table2: Design parameters

Bean pipe radius	b=17.5mm
Longitudinal length	25mm
Electrode deviation angle from horizontal axis	ϕ=30 degrees
Feedthrough impedance	Z=50Ω
Electrode thickness	L=1.5mm
Electrode radius	a=5mm
Gap between electrode and vacuum	w=0.3mm

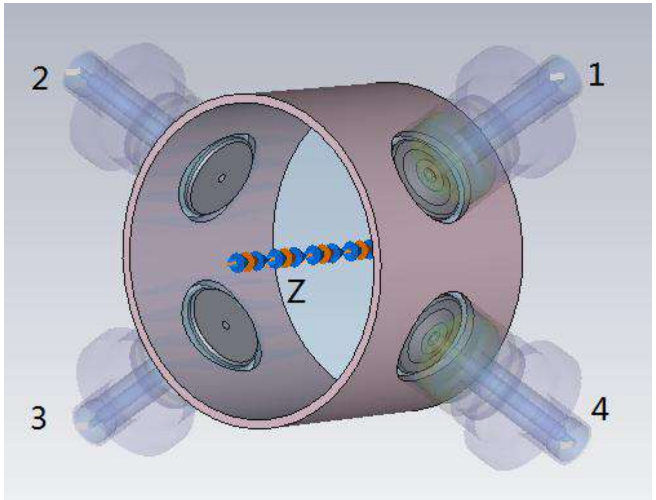


Fig.1 3-D model

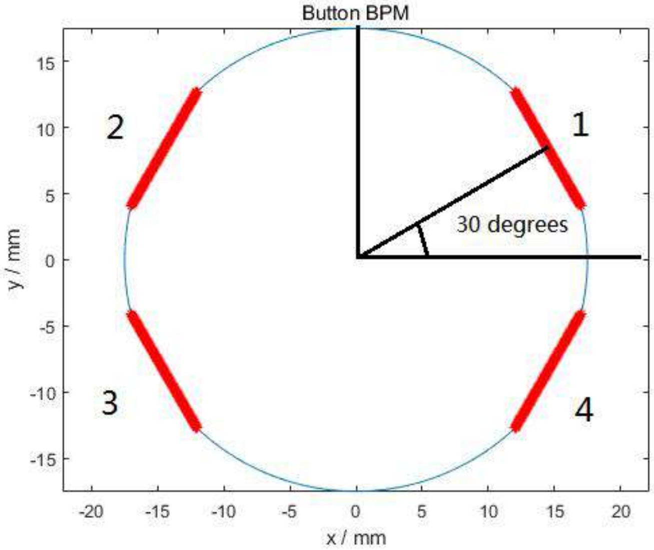
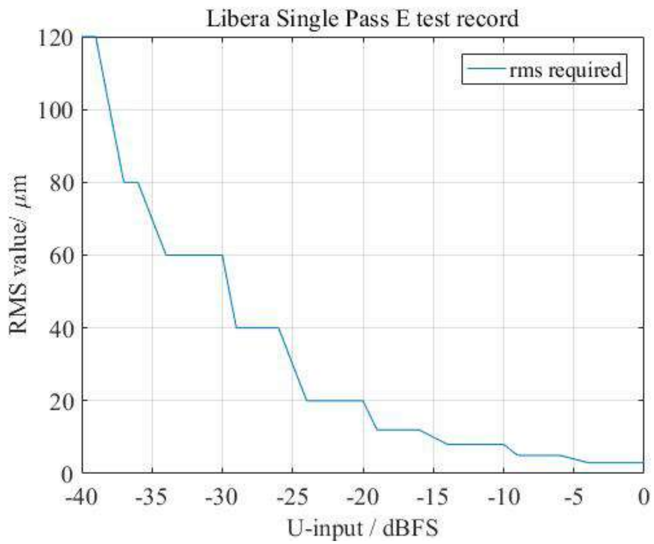


Fig.2 Cross section view

2. Design of Button BPM

Fig.3 RMS value <—>input signal level



Back-end electronics:

Libera Single Pass E
(Central frequency: 476MHz)

Assuming the biggest movable range for x and y directions:

-5 —> +5 mm

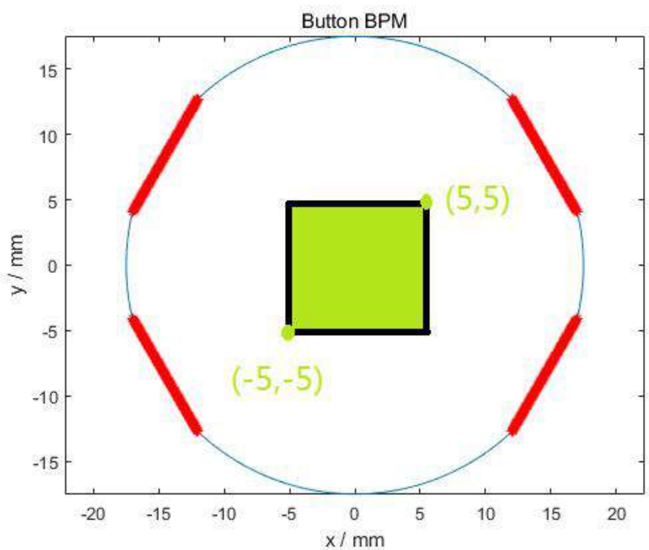


Fig.4 Calculation region(green)

2. Design of Button BPM

Follow signal from beam pipe to the Libera Single Pass E:

Bunch current: $$I(t) = \frac{Q}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}}$$

Image charge on button: $$Q_{imag}(\omega) = \frac{S_{button}}{C_{vacuum}} \cdot \frac{I(\omega)}{\beta c} = \frac{\pi a^2}{2\pi b} \cdot \frac{I(\omega)}{\beta c}$$

Image current on button: $$I_{imag}(\omega) = \frac{\pi a^2}{2\pi b} \cdot \frac{i\omega}{\beta c} \cdot I(\omega)$$

Equivalent resistance: $$Z(\omega) = (Z^{-1} + i\omega C)^{-1} \qquad C = \frac{2\pi\varepsilon_0 L}{\ln\left(\frac{r+w}{r}\right)}$$

Image voltage on button: $$V(\omega) = I_{imag}(\omega) \cdot Z(\omega)$$

Attenuation of coax-cable LMR-400: $$Att. = -0.033 \cdot L_{cable} \cdot \left(0.12229\sqrt{F_{MHz}} + 0.00026 F_{MHz}\right)$$

Voltage out of cable: $$V_{cable}(\omega) = V(\omega) \cdot 10^{\frac{Att.}{20}}$$

Ref: Smith S R. Beam position monitor engineering. AIP Conference Proceedings. AIP, 1997, 390(1): 50-65.

2. Design of Button BPM

$$Q_{imag}(\omega) = \frac{S_{button}}{C_{vacuum}} \cdot \frac{I(\omega)}{\beta c} = \frac{\pi a^2}{2\pi b} \cdot \frac{I(\omega)}{\beta c}$$

a—> button radius

b—>beam pipe radius

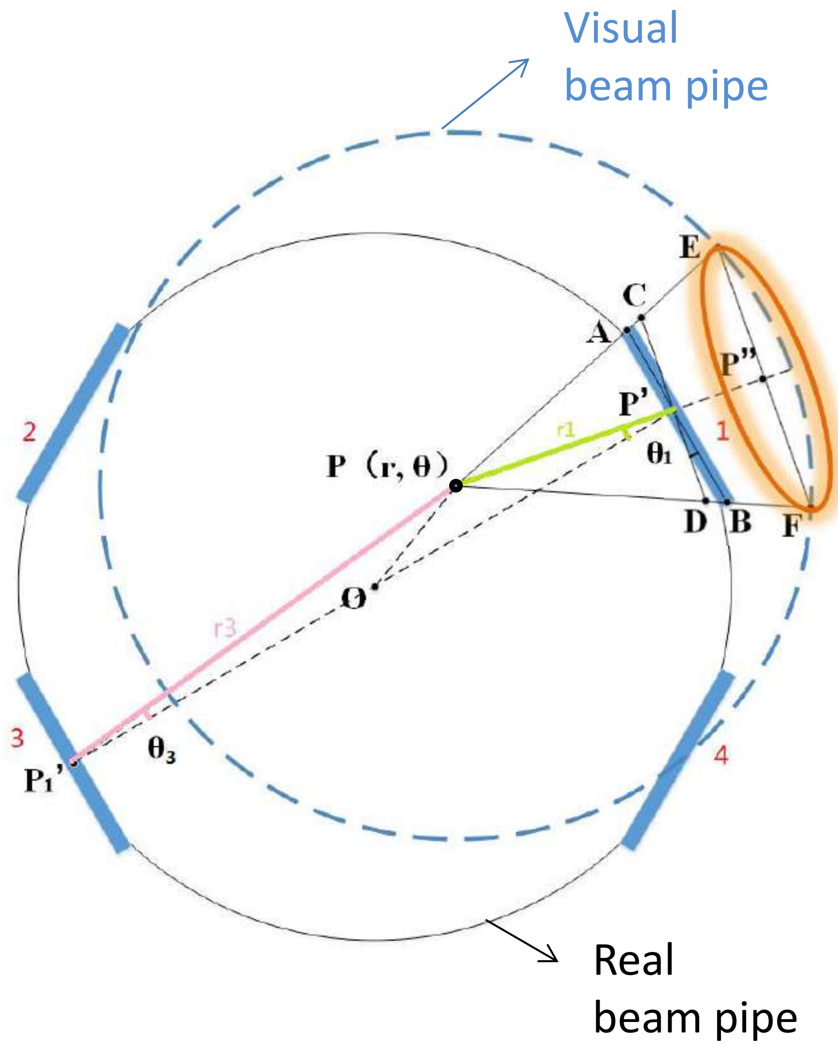
beam at (0,0):

$$S_{button} = \pi \cdot a^2$$

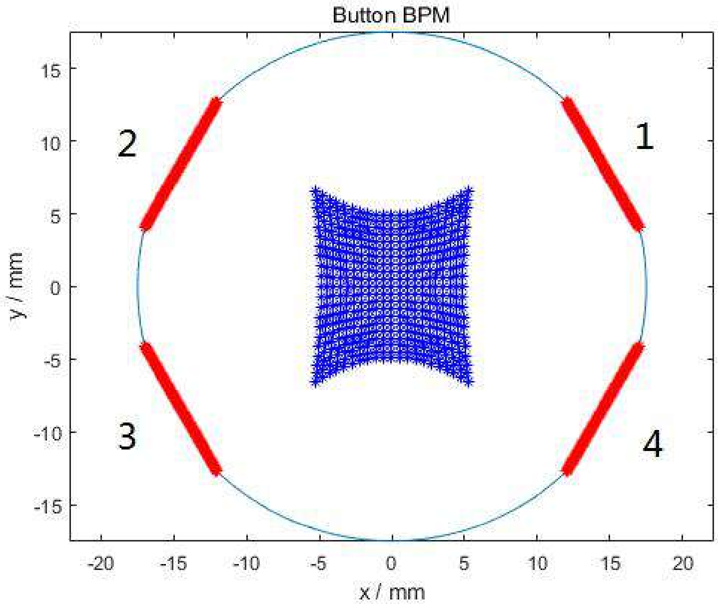
beam at P(r,θ):

for Button i (i=1,2,3,4)

$$S_{button}^{\ i} = \frac{\pi a^2 b^2 \cos(\theta_i)}{ri^2}$$



2. Design of Button BPM



Delta over Sum

$$U_{\Delta/\Sigma} = \frac{Q_1 + Q_4 - Q_2 - Q_3}{Q_1 + Q_2 + Q_3 + Q_4}$$

$$V_{\Delta/\Sigma} = \frac{Q_1 + Q_2 - Q_3 - Q_4}{Q_1 + Q_2 + Q_3 + Q_4}$$

Linear fitting

$$x = K_x \cdot U_{\Delta/\Sigma} + X_m$$

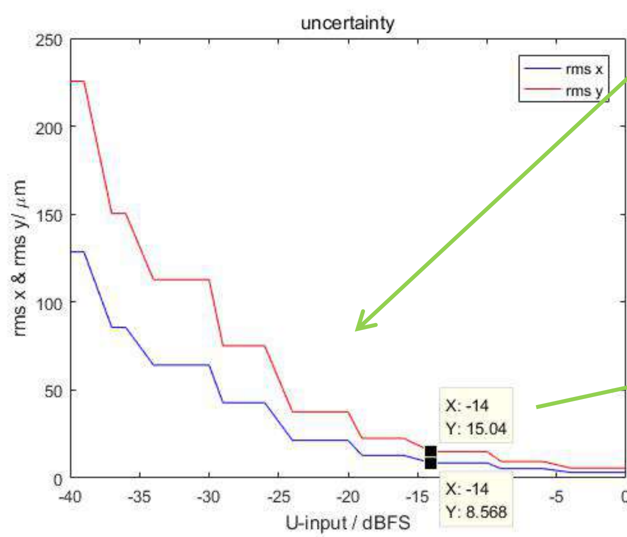
$$y = K_y \cdot V_{\Delta/\Sigma} + Y_m$$

Region: (-5,-5)~(5,5)mm	Kx / mm	Ky / mm
Boundary element method	10.6928	18.2625
Derived formula	10.7095	18.8019
Error / %	0.156%	2.954%

Ref: Shintake, Tsumoru, et al. Sensitivity calculation of beam position monitor using boundary element method. *NIMPRSA:* (1987): 146-150.

2. Design of Button BPM

Condition : Q=1nC, bunch length=5ps , macro pulse length=5μs, cable length=80m					
Bunch repeat frequency		**59.5 MHz**	**119 MHz**	**238 MHz**	**476 MHz**
Signal level	**maximum**	-16.0441dBm	-10.0296dBm	-4.0115dBm	2.0122dBm
	minimum	-30.0605dBm	-24.0424dBm	-18.0249dBm	-12.00425dBm
Signal range \ dB		-14.0164	-14.0128	-14.0134	-14.0164



Libera single pass E Required RMS noise

(1) **Resolution induced by electronics**

σx1/μm	8.651
σy1/μm	15.04

2. Design of Button BPM

(2) **Intrinsic resolution** only considering thermal noise:

$$\sigma_{int} = \frac{b}{2\sqrt{2}} \cdot \frac{1}{\sqrt{SNR}}, SNR = \frac{P_{signal}}{P_{noise}}, P_{noise} = kTB_W$$

$$k = 1.3806 \times 10^{-23} J/K, T = 300K, B_W = 10MHz$$

Bunch repetition rate		59.5 MHz	119 MHz	238 MHz	476 MHz
Intrinsic resolution	σx2=σy2/μm	0.3263	0.1635	0.0817	0.0409

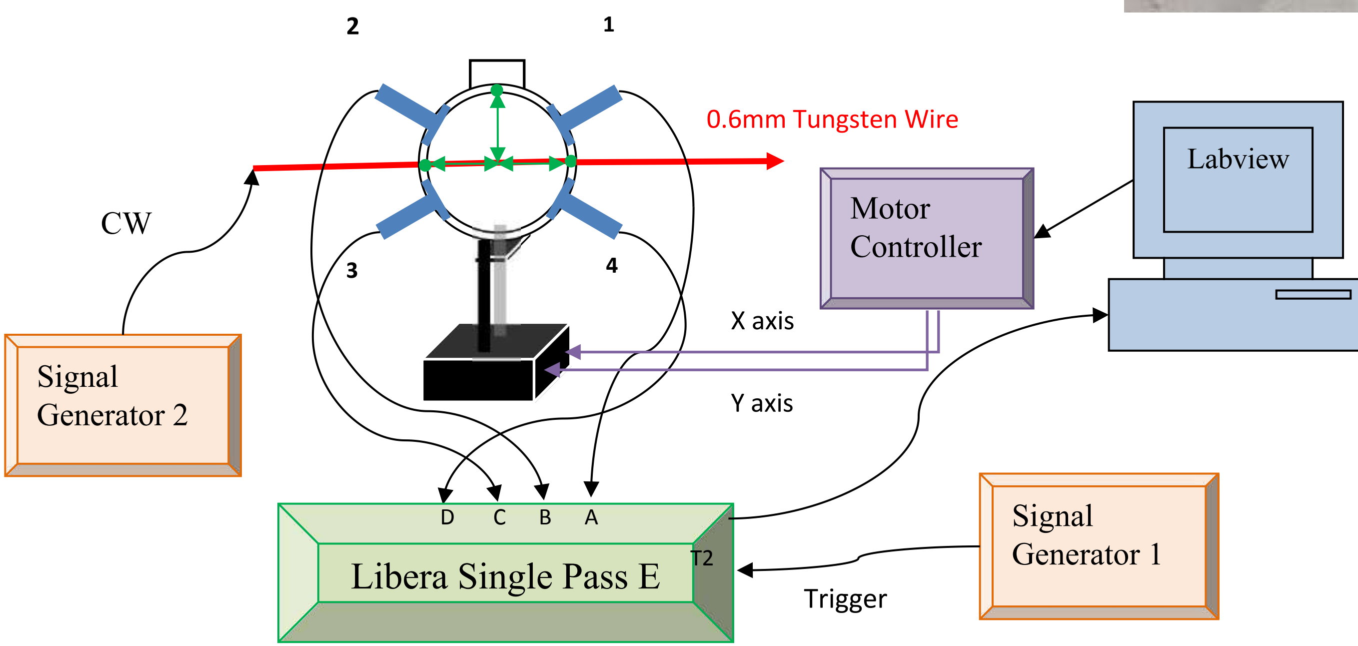
$$\sigma_x = \sqrt{\sigma_{x1}^2 + \sigma_{x2}^2} \qquad \sigma_y = \sqrt{\sigma_{y1}^2 + \sigma_{y2}^2}$$

Resolution	σx/μm	8.6572	8.6525	8.6514	8.6511
	σy/μm	15.0435	15.0409	15.0402	15.0401

3. Offline tests

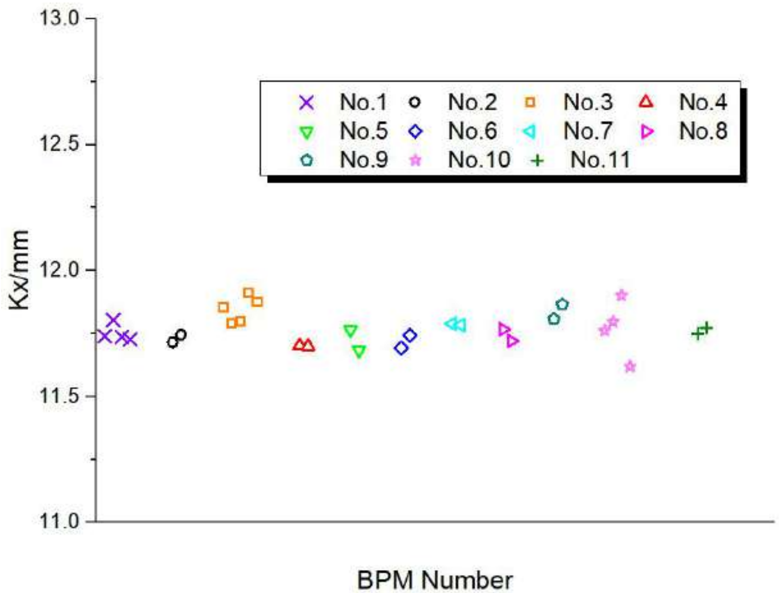
Wire Method

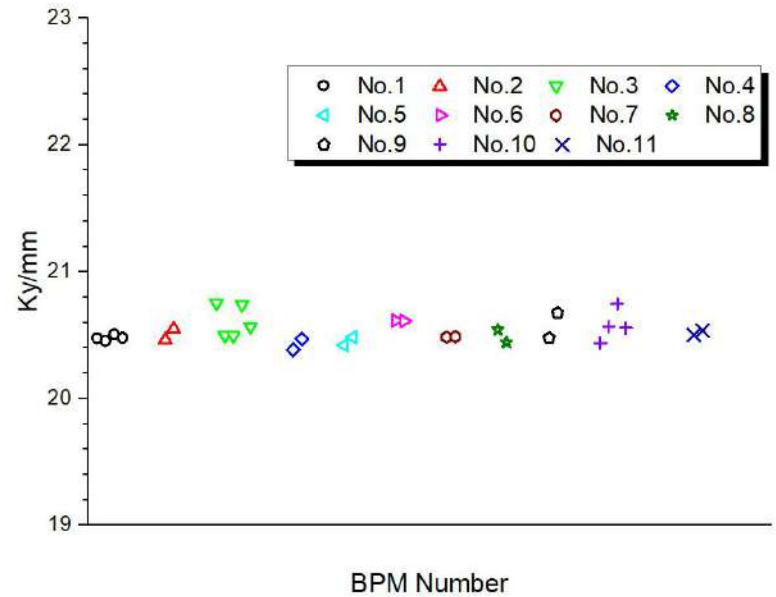
1. X Y moving range : -5mm~+5mm , step : 0.5mm
2. X-Y motor： position resolution = 2.5μm



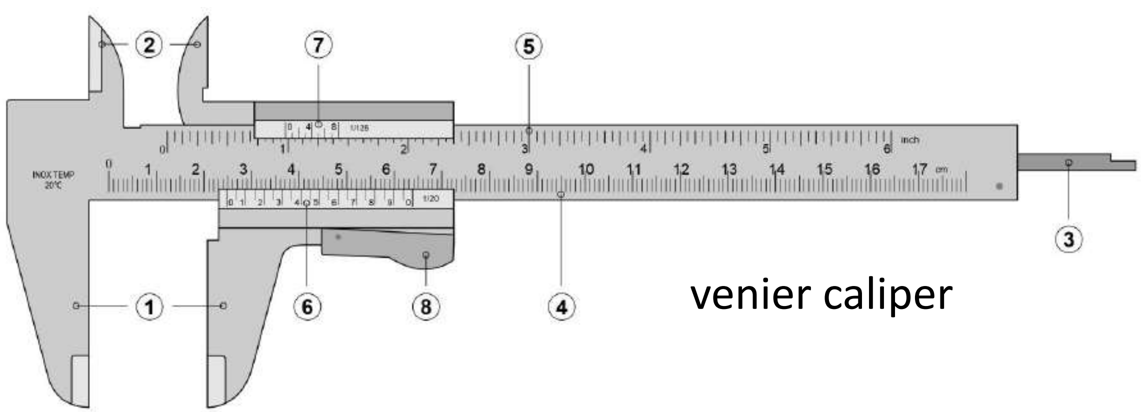
3. Offline tests

Results for multiple tests with all 11 BPMs





deviation within 5%

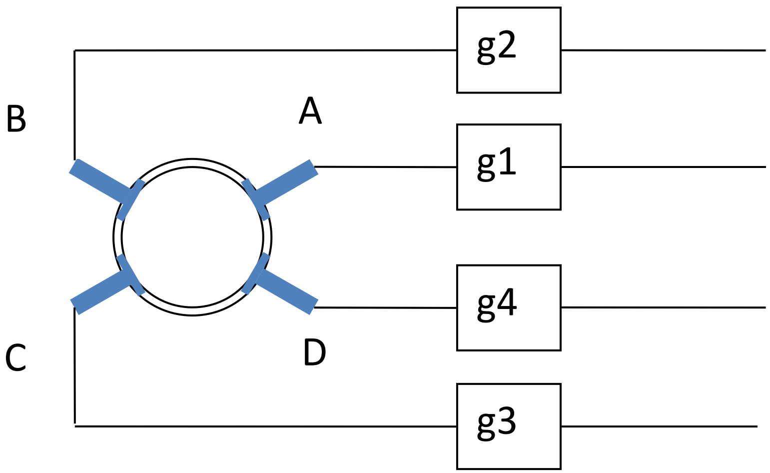


venier caliper

search for mechanical center

3. Offline tests

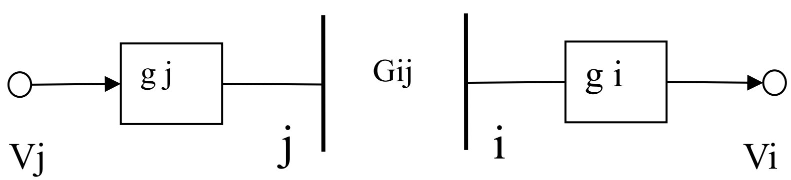
Lambertson Method



The mechanical center offset relative to the electrical center :

$$X_m = K_x \cdot \frac{g_1 + g_4 - g_2 - g_3}{g_1 + g_2 + g_3 + g_4} = K_x \cdot \frac{1 + g_{41} - g_{21} - g_{31}}{1 + g_{21} + g_{31} + g_{41}}$$

$$Y_m = K_y \cdot \frac{g_1 + g_2 - g_3 - g_4}{g_1 + g_2 + g_3 + g_4} = K_y \cdot \frac{1 + g_{21} - g_{31} - g_{41}}{1 + g_{21} + g_{31} + g_{41}}$$



$$S_{ij} = V_{ij} = \frac{V_i}{V_j} = 2 \cdot 50 \cdot G_{ij} \cdot g_i \cdot g_j$$

$$V_j^B = 2 \cdot g_j \cdot V_j \Rightarrow I_i = G_{ij} \cdot V_j^B \Rightarrow V_i = 2 \cdot 50 \cdot G_{ij} \cdot g_i \cdot g_j \cdot V_j$$

Ref: Chung, Y., & Decker, G. Offset calibration of the beam position monitor using external means. *AIP Conference Proceedings* (Vol. 252, No. 1, pp. 217-224).

3. Offline tests

Assuming:

$$G_{ij}=G_{ji}$$
$$G_{12}=G_{34}$$
$$G_{13}=G_{24}$$
$$G_{23}=G_{14}$$

$\Rightarrow$

$$2\cdot 50\cdot g_1^{\;2}=\frac{S_{21}S_{12}}{S_{42}}\cdot\frac{G_{13}}{G_{12}G_{23}}=\frac{S_{12}S_{31}}{S_{32}}\cdot\frac{G_{23}}{G_{12}G_{13}}=\frac{S_{41}S_{31}}{S_{43}}\cdot\frac{G_{12}}{G_{23}G_{13}}$$
$$2\cdot 50\cdot g_2^{\;2}=\frac{S_{21}S_{32}}{S_{31}}\cdot\frac{G_{13}}{G_{12}G_{23}}=\frac{S_{21}S_{42}}{S_{14}}\cdot\frac{G_{23}}{G_{12}G_{13}}=\frac{S_{32}S_{42}}{S_{43}}\cdot\frac{G_{12}}{G_{23}G_{13}}$$
$$2\cdot 50\cdot g_3^{\;2}=\frac{S_{32}S_{43}}{S_{42}}\cdot\frac{G_{13}}{G_{12}G_{23}}=\frac{S_{43}S_{31}}{S_{14}}\cdot\frac{G_{23}}{G_{12}G_{13}}=\frac{S_{32}S_{31}}{S_{21}}\cdot\frac{G_{12}}{G_{23}G_{13}}$$
$$2\cdot 50\cdot g_4^{\;2}=\frac{S_{43}S_{14}}{S_{31}}\cdot\frac{G_{13}}{G_{12}G_{23}}=\frac{S_{43}S_{42}}{S_{32}}\cdot\frac{G_{23}}{G_{12}G_{13}}=\frac{S_{14}S_{42}}{S_{21}}\cdot\frac{G_{12}}{G_{23}G_{13}}$$

$\Downarrow$

$$g_{21}=\frac{g_2}{g_1}=\sqrt{\frac{S_{32}S_{42}}{S_{31}S_{14}}}=\sqrt{\frac{S_{21}S_{42}S_{32}}{S_{12}S_{14}S_{31}}}=\sqrt{\frac{S_{32}S_{42}}{S_{41}S_{31}}}$$
$$g_{31}=\frac{g_3}{g_1}=\sqrt{\frac{S_{32}S_{43}}{S_{21}S_{14}}}=\sqrt{\frac{S_{43}S_{32}}{S_{12}S_{14}}}=\sqrt{\frac{S_{32}S_{43}}{S_{41}S_{21}}}$$
$$g_{41}=\frac{g_4}{g_1}=\sqrt{\frac{S_{42}S_{43}}{S_{31}S_{21}}}=\sqrt{\frac{S_{14}S_{42}S_{43}}{S_{21}S_{41}S_{31}}}=\sqrt{\frac{S_{42}S_{43}}{S_{12}S_{31}}}$$

$\Leftarrow$

Lambertson Method

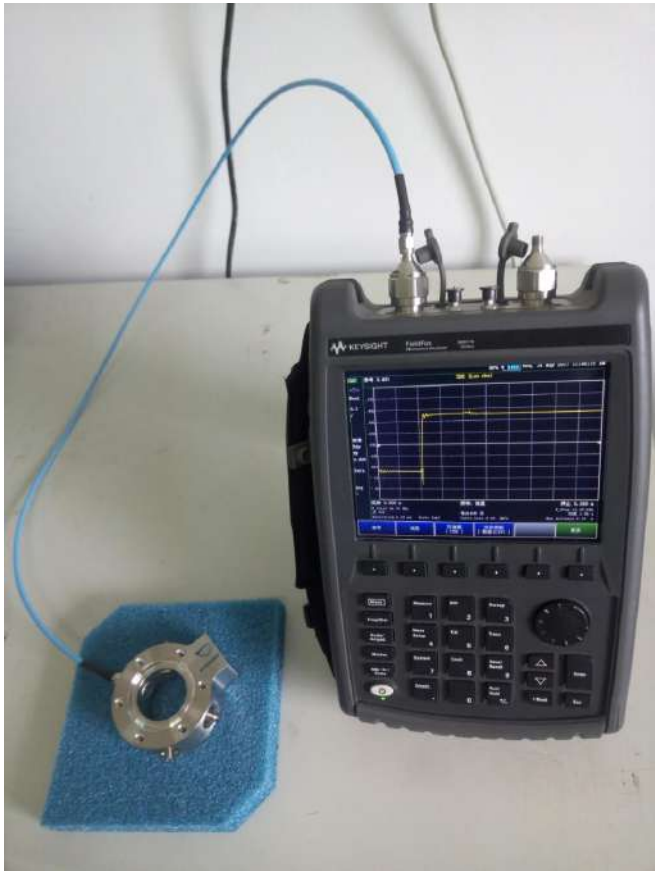
$$X_m=K_x\cdot\frac{1+g_{41}-g_{21}-g_{31}}{1+g_{21}+g_{31}+g_{41}}$$
$$Y_m=K_y\cdot\frac{1+g_{21}-g_{31}-g_{41}}{1+g_{21}+g_{31}+g_{41}}$$

Ref: Chung, Y., & Decker, G. Offset calibration of the beam position monitor using external means. *AIP Conference Proceedings* (Vol. 252, No. 1, pp. 217-224).

3. Offline tests

Lambertson method's Precondition:

Each BPM has four electrodes with good Consistency

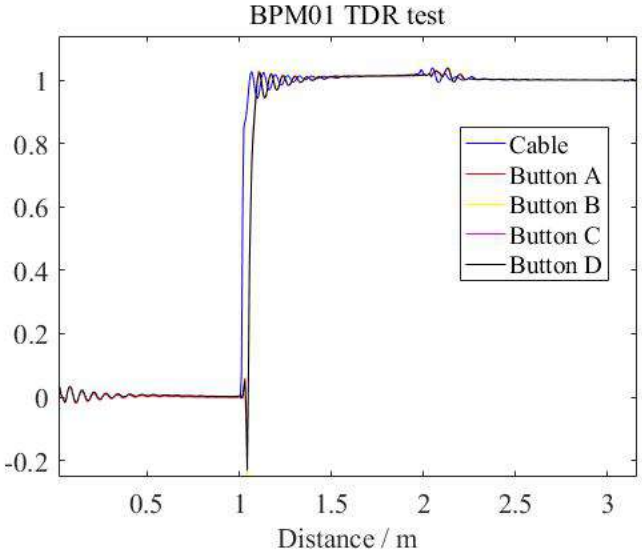


TDR-test:

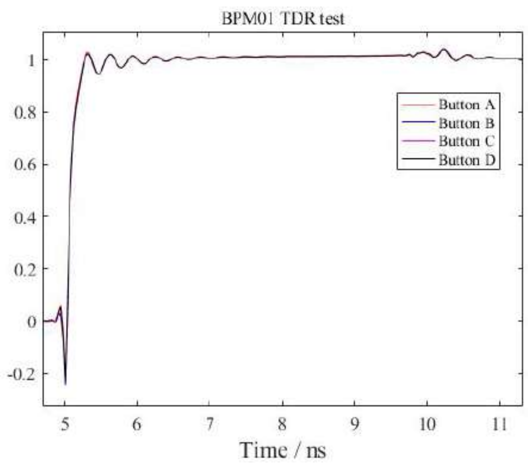
Cable version: Tflex-402

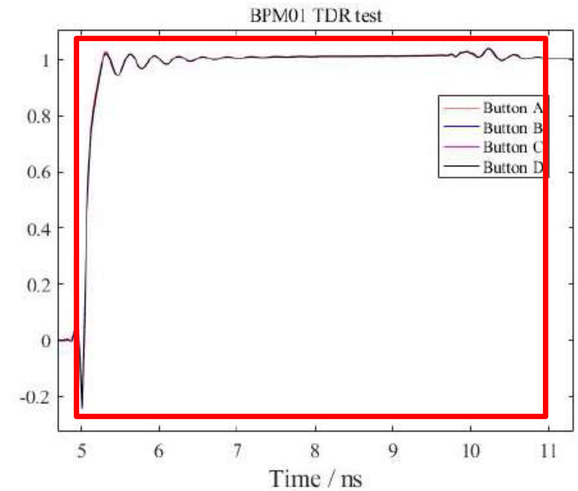
Length: ~1m

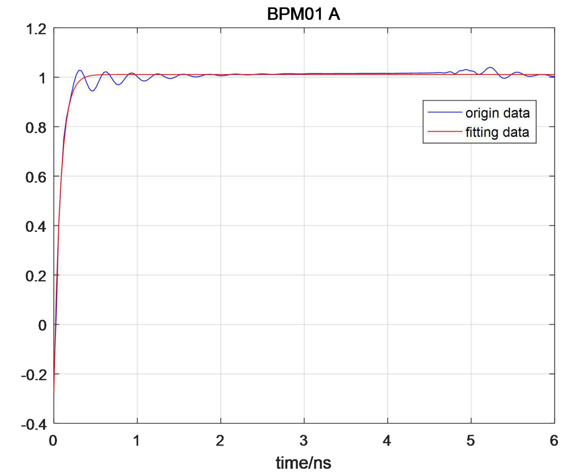
Velocity: ~0.695*c



3. Offline tests







Fitting equation:

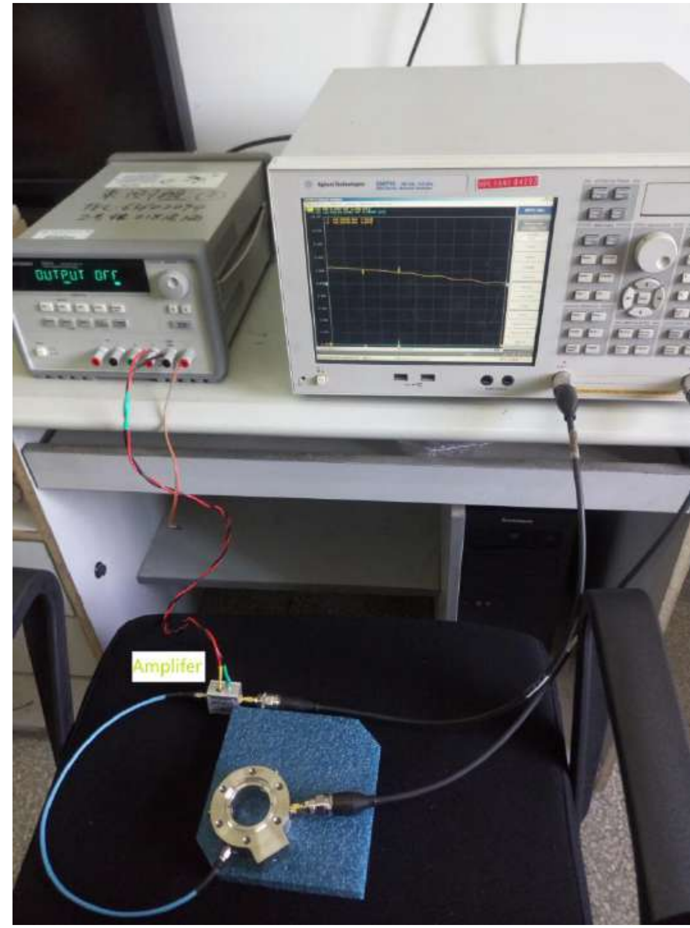
$$y = a1 + a2 \cdot e^{-a3 \cdot t}$$

a3= 1/(R*C)

Capacitance / pF	A	B	C	D	Theoretical value
BPM# 1	1.5765	1.5580	1.5867	1.5937	1.4321
BPM# 9	1.5339	1.5431	1.5397	1.5393	

3. Offline tests

BPM Number		Lambertson method f=476MHz	
		Xm /µm	Ym /µm
No.1	1#	234.7	-171.1
	2#	258.1	-138.7
No.9	1#	-145.5	-380.2
	2#	-157.0	-213.7



Not enough tests to get a general Conclusion!

4. Conclusion and Outlook

1. Kx & Ky both have ~9% deviation from the theoretical value.
2. **How to improve the precision of wire method?**

The end!