미래기반 가속기
전문인력양성 사업단

특론: 가속기 실험실습 I

(NUCE719P-01/PHYS715P-01, 정모세)

PAL-XFEL Diagnostics & Beam Position Monitor

김 창 범

포항가속기연구소
PLS-II 가속장치부

Introduction

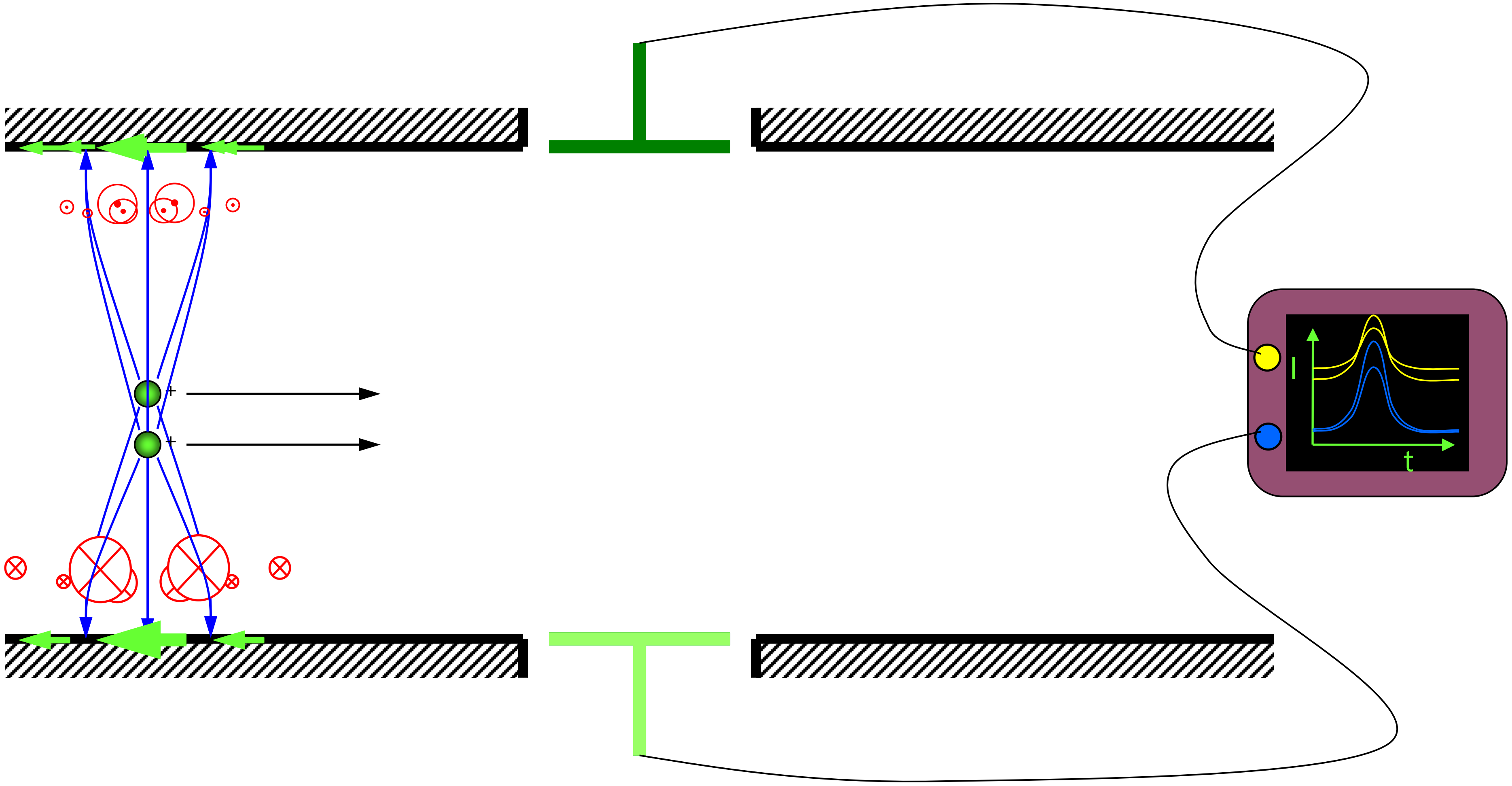
- Beam goes inside vacuum chamber literally not visible from outside
- Cannot get close to accelerator during operation
- Need to equip accelerator with monitoring equipment to measure key parameters of beam
- Beam instrumentation are the 'eyes and ears' of accelerators.

Diagnostics for PAL-XFEL

Parameter	Instruments	Number	Resolution
Beam Position & Beam Energy	Stripline BPM	160	< 5 um
	Cavity BPM	49	< 1 um
Beam Size	Screen Monitor	54	< 10 um
	Wire Scanner	9	< 10 um
Bunch Length	Coherent Radiation Monitor	4	-
	Transverse Deflecting Cavity	3	< 10 fs
Beam Charge	Turbo ICT	10	< 1 pC
Beam Arrival Time	Beam Arrival Time Monitor	10	< 30 fs
Beam Loss	Beam Loss Monitor	26	-

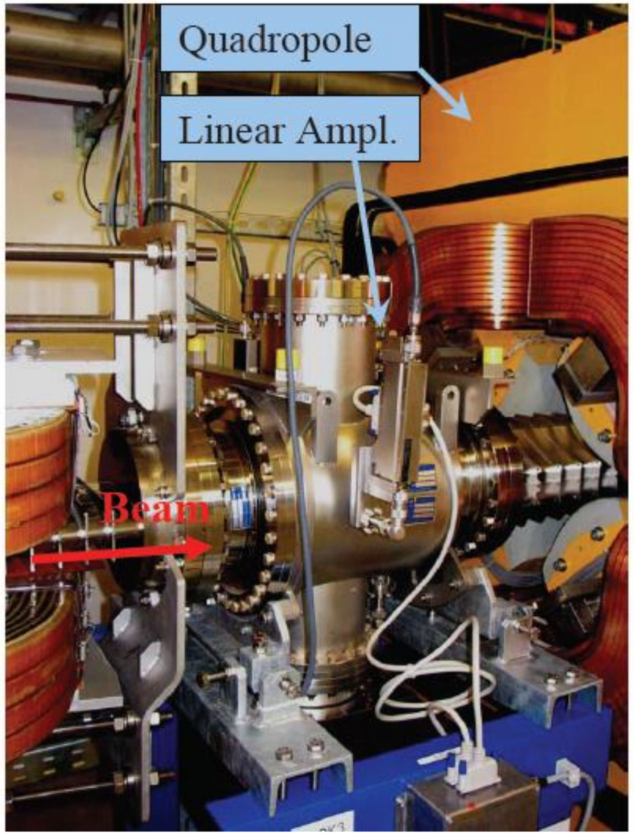
Beam Position Monitor (BPM)

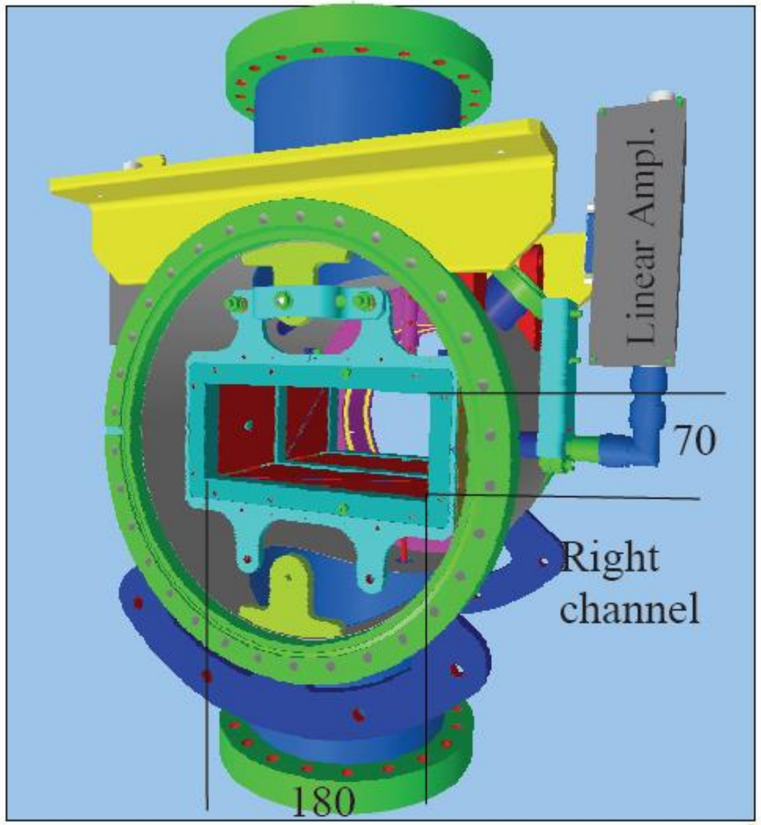
Working Principle of Beam Position Monitor (BPM)

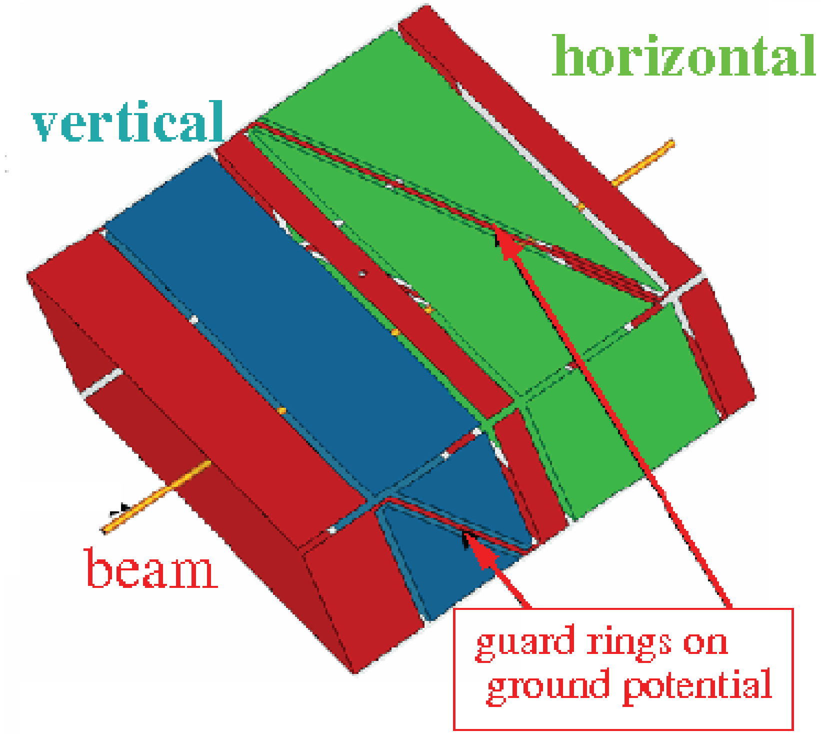


Shoe Box BPM

Shoe Box BPM

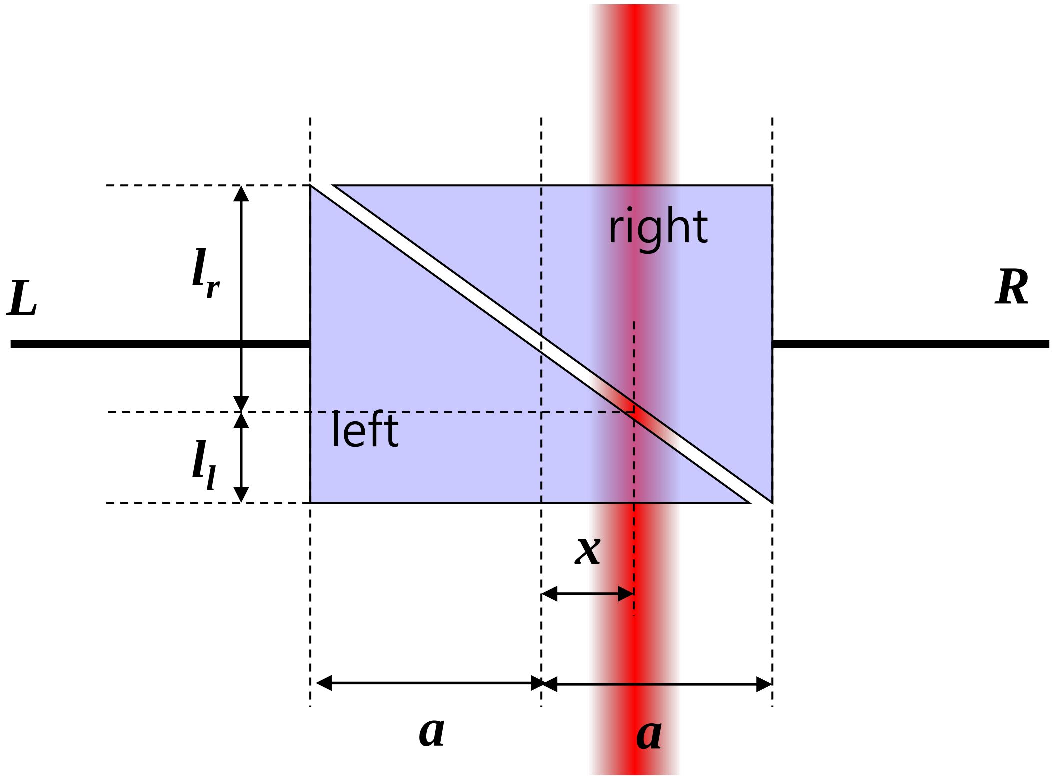






P. Forck, CAS 'Diagnostics'

Beam Position Measurement



- Signals L, R are proportional to plate length 'seen' by beam

$$L \propto l_l, \quad R \propto l_r$$

$$l_l = (a - x)\cdot \tan\alpha, \; l_r = (a + x)\cdot \tan\alpha$$

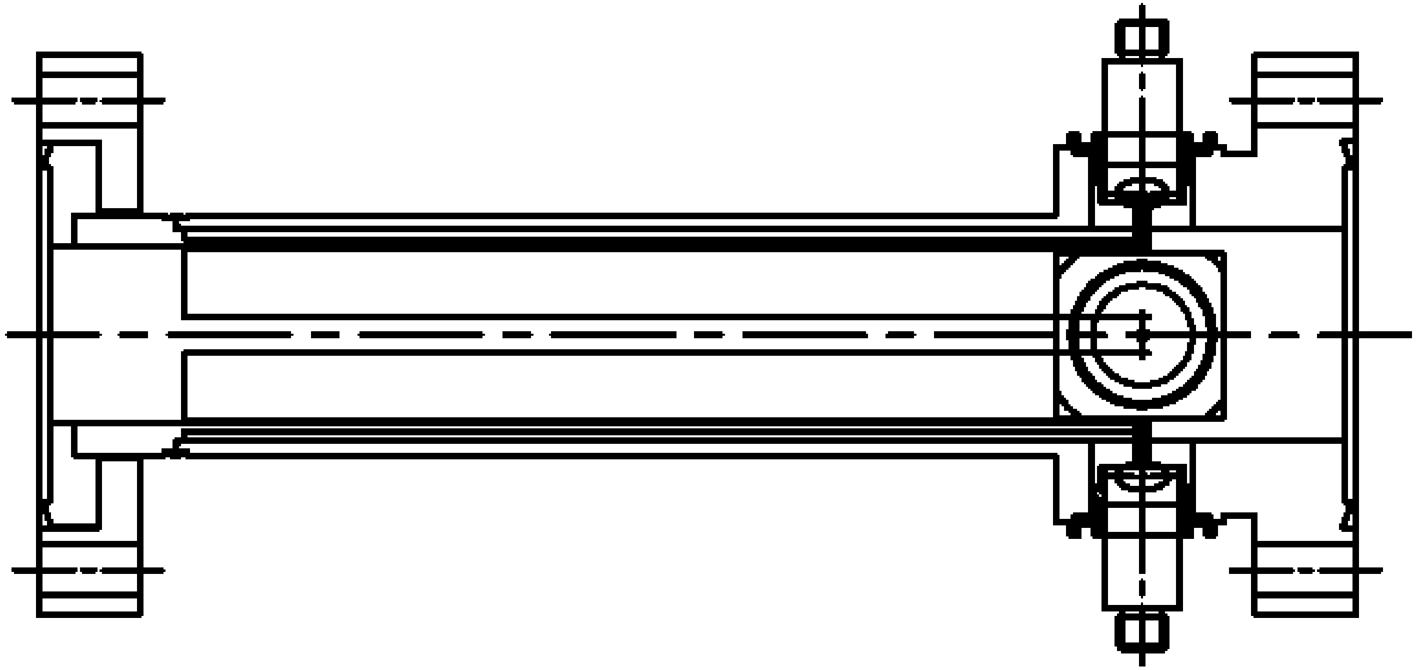
$$\Rightarrow \frac{l_r - l_l}{l_r + l_l} = \frac{x}{a} \quad \Rightarrow \quad x = a\cdot\frac{R-L}{R+L}$$

Summary of Shoe Box BPM

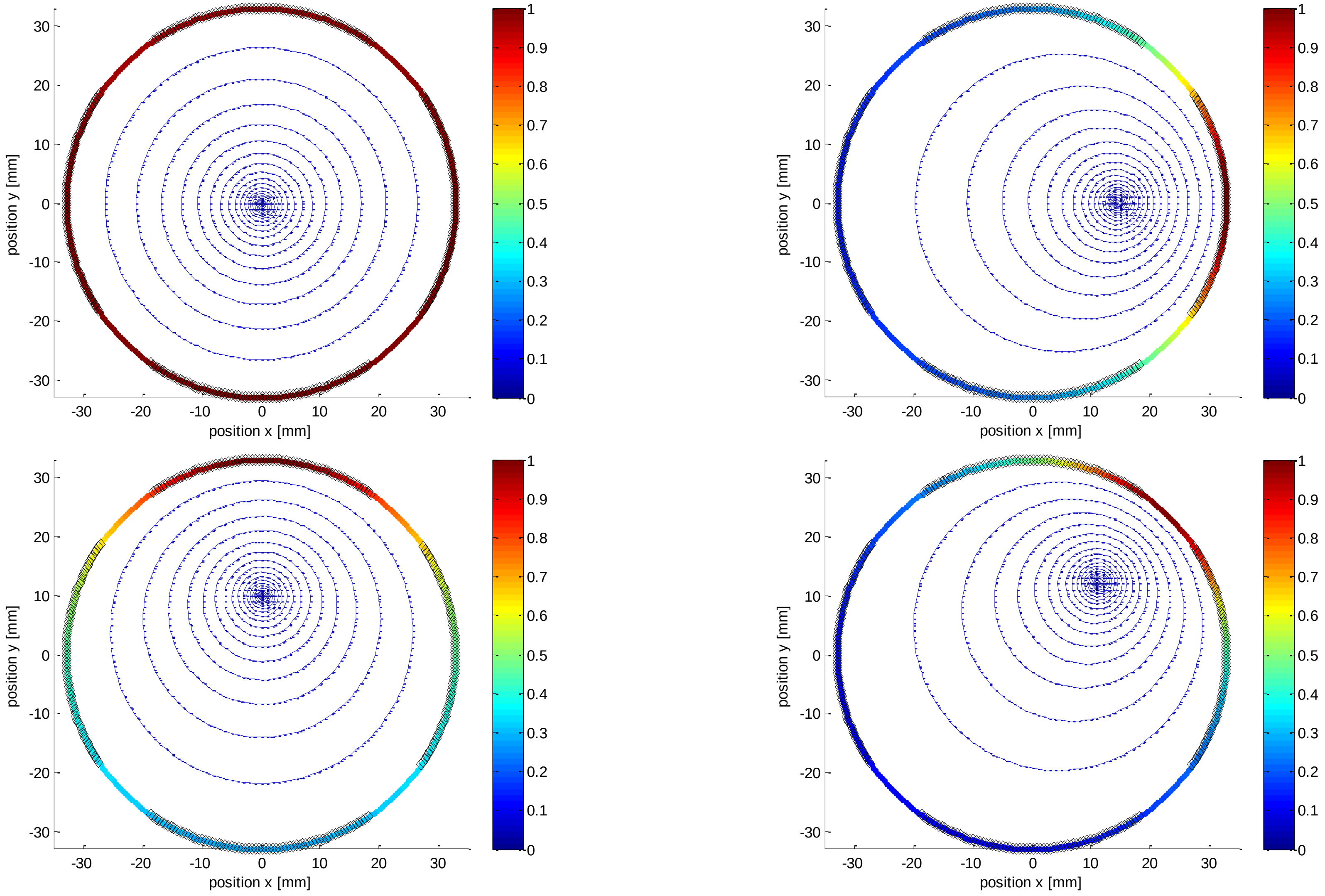
- Very good linearity and low x/y coupling
- Bunch length longer than BPM (10~20 cm per plane)
- Bandwidth 0.1~100 MHz
- Used mainly in low energy hadron machines

Stripline BPM

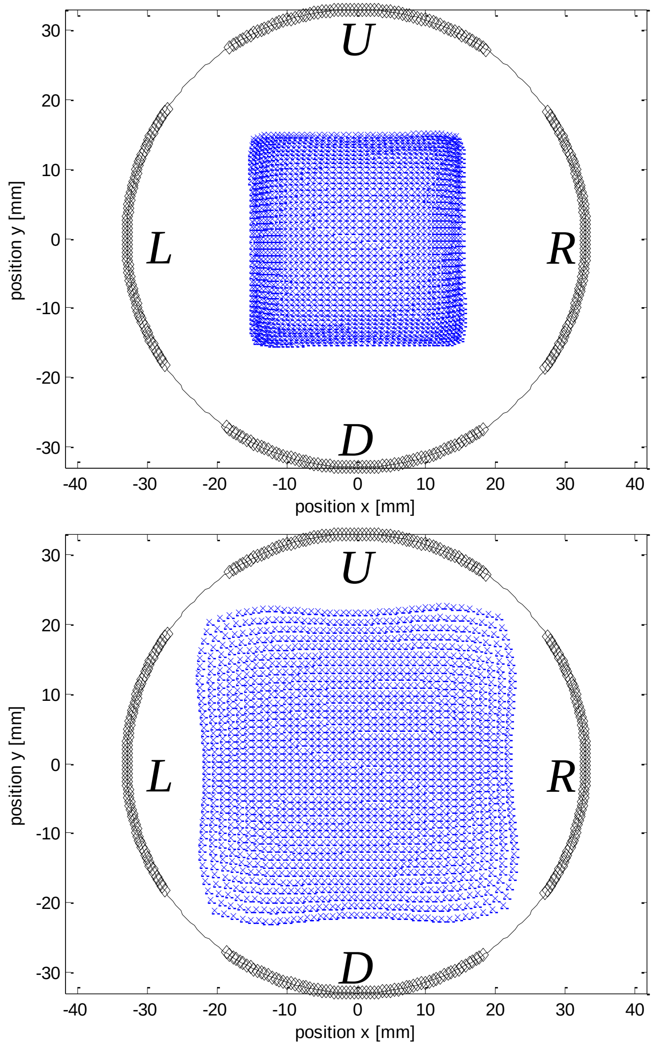
Stripline BPM



Charge Distribution in Round Beam Tube



Position Calculation from Pickup Signals

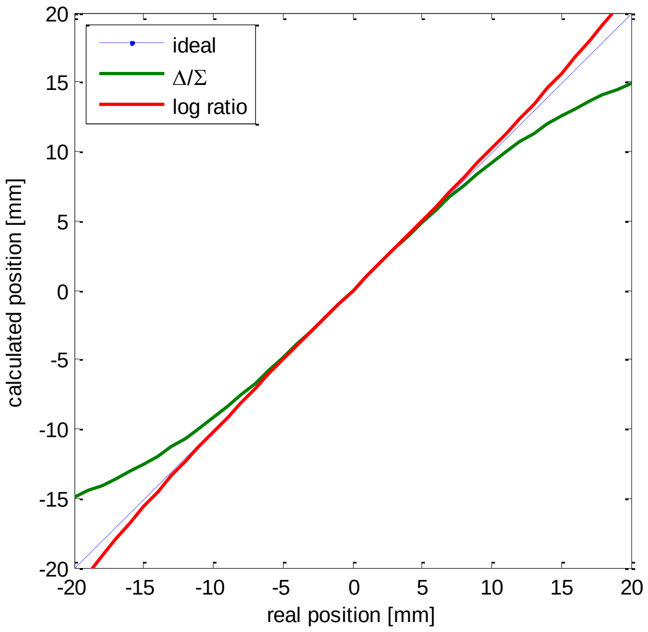


$$x = k_x \cdot \frac{R-L}{R+L}$$

$$y = k_y \cdot \frac{U-D}{U+D}$$

$$x = k_x \cdot \log\left(\frac{R}{L}\right)$$

$$y = k_y \cdot \log\left(\frac{U}{D}\right)$$



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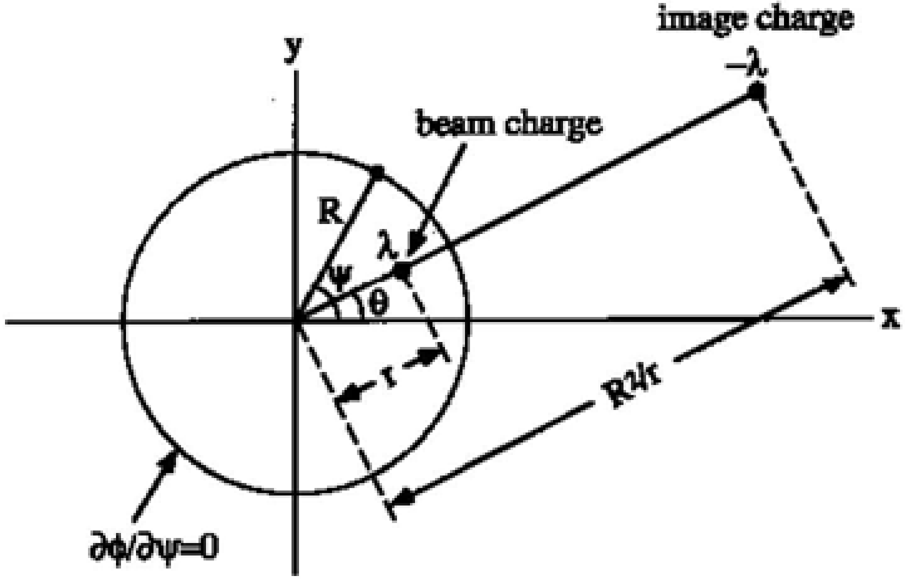
Beam Induced Charge on Cylindrical Pipe

Charge distribution on the pipe surface can be calculated by using mirror charge.

$$\sigma(R,\phi) = -\frac{\lambda}{2\pi R}\cdot\frac{R^2 - r^2}{R^2 + r^2 - 2rR\cos(\phi-\theta)}$$

$$= -\frac{\lambda}{2\pi R}\left\{1 + 2\sum_{n=1}^{\infty}\left(\frac{r}{R}\right)^n \cos n(\phi-\theta)\right\}$$

λ : line charge density of the pencil beam at (r,θ)



IBIC2012, Tsukuba

Beam Induced Charge on Stripline Electrodes

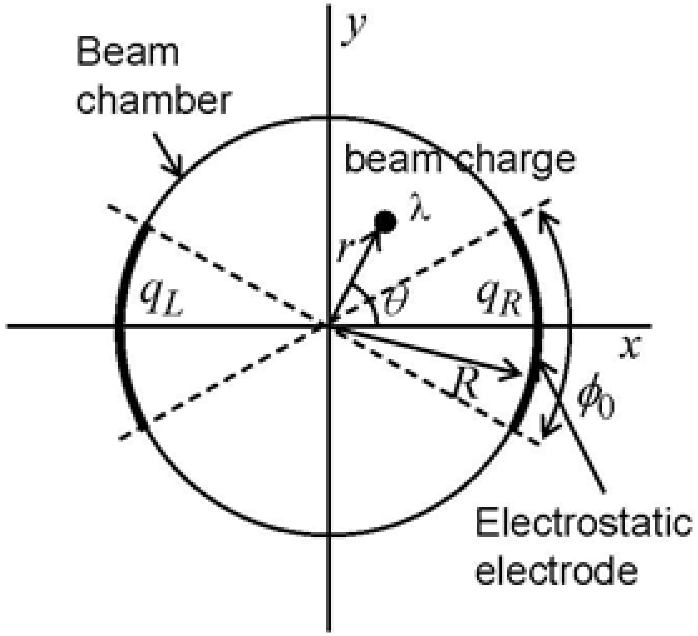
Induced charge on parallel-plate electrodes:

$$q_R = \int_{-\phi_0/2}^{\phi_0/2} \sigma(R,\phi) R d\phi$$

$$= -\frac{\lambda}{2\pi}\left\{\phi_0 + 4\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{R}\right)^n \sin\left(\frac{n\phi_0}{2}\right)\cos n\theta\right\}$$

$$q_L = \int_{\pi-\phi_0/2}^{\pi+\phi_0/2} \sigma(R,\phi) R d\phi$$

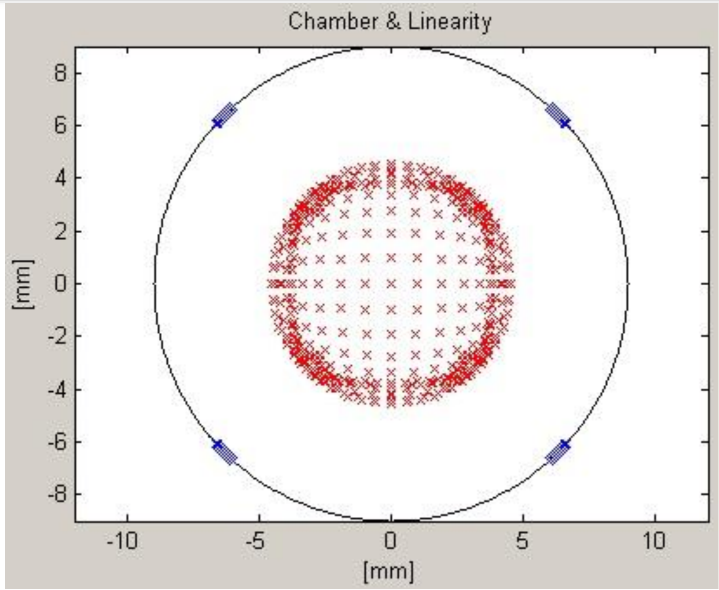
$$= -\frac{\lambda}{2\pi}\left\{\phi_0 + 4\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{R}\right)^n \sin\left\{n\left(\pi+\frac{\phi_0}{2}\right)\right\}\cos n\theta\right\}$$



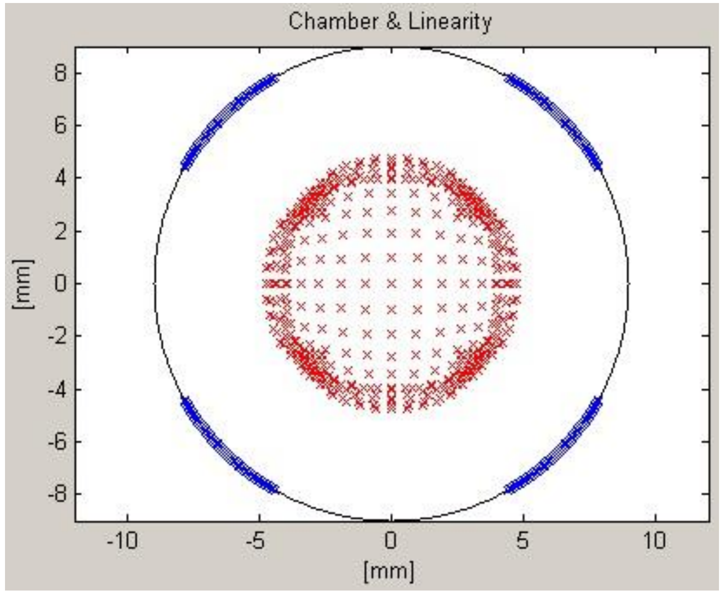
Induced signal voltages are expected to be :

$$V_R \propto q_R, \quad V_L \propto q_L$$

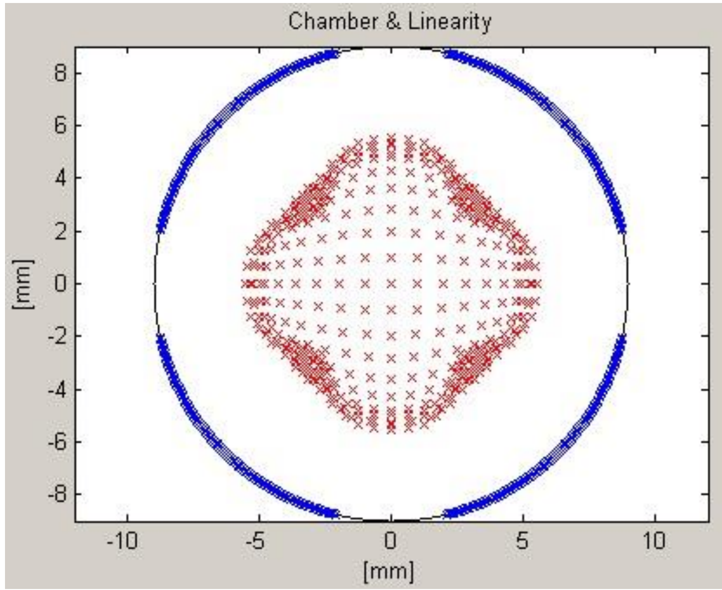
Linearity



1 mm Stripline width

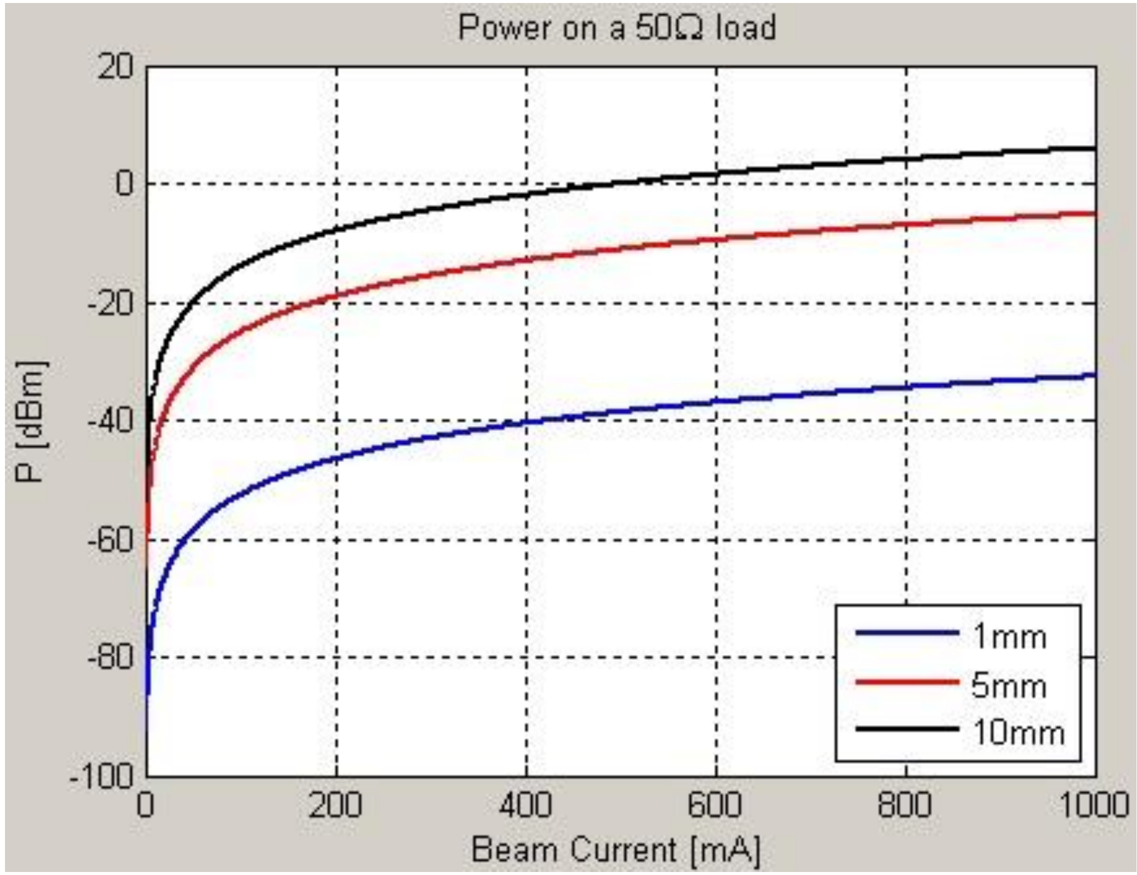


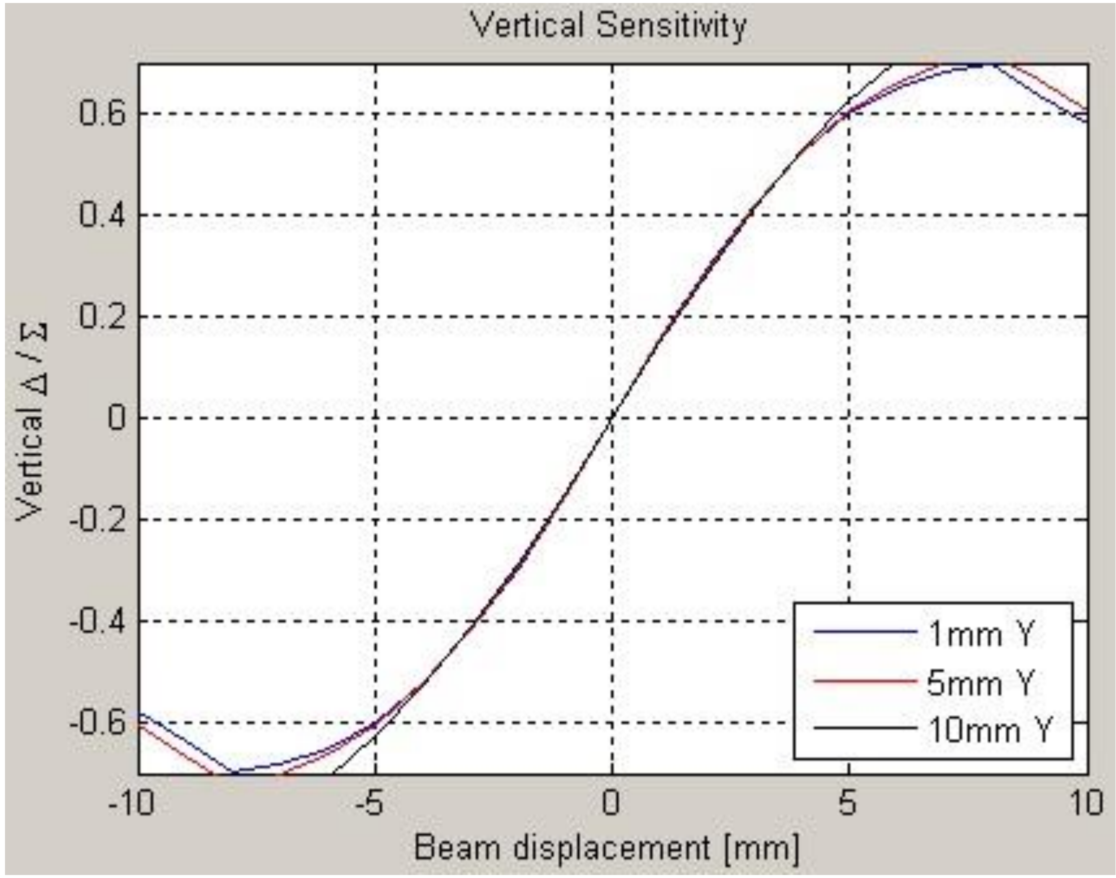
5 mm Stripline width



10 mm Stripline width

Sensitivity & Power





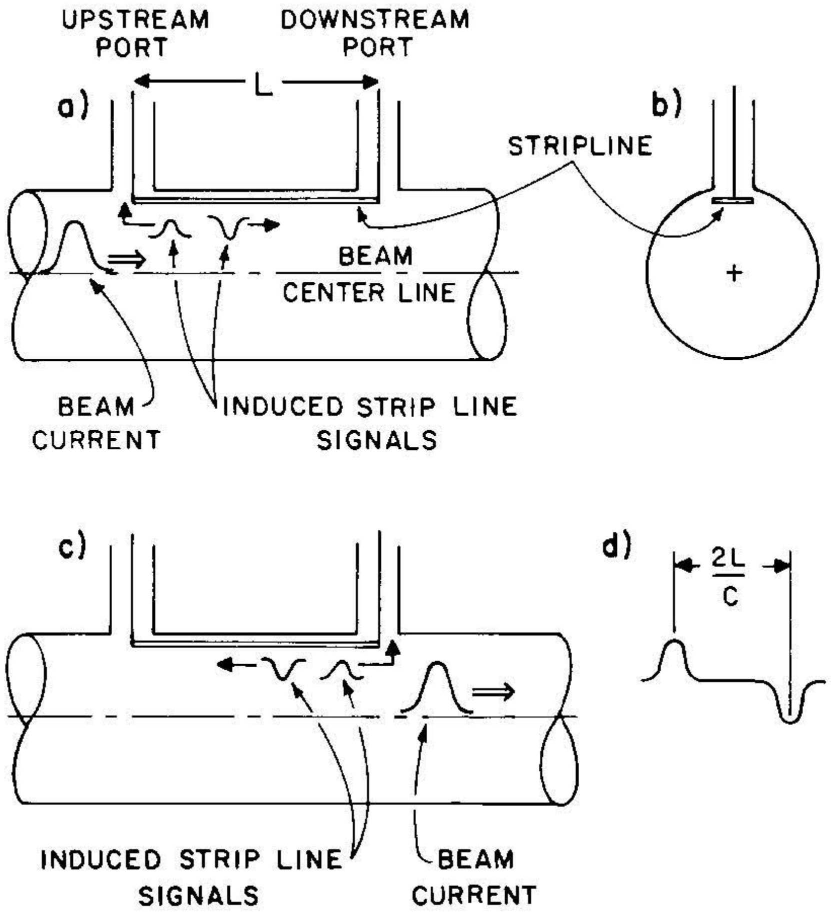


Fig. 1. Strip line beam position monitor. (a) Side view of monitor with the beam pulse shown arriving at the beginning of the strip line. (b) End view of monitor. (c) Side view of monitor with beam shown just after it passes the strip line. (d) Induced signal as observed on the upstream port. (Please note that in (a) and (c) the temporal relationship between the induced signals and the beam is only shown schematically. The signals are induced coincident in time with the beam passage. The signal on the strip line travels down the line coincident with the beam moving down the pipe.)

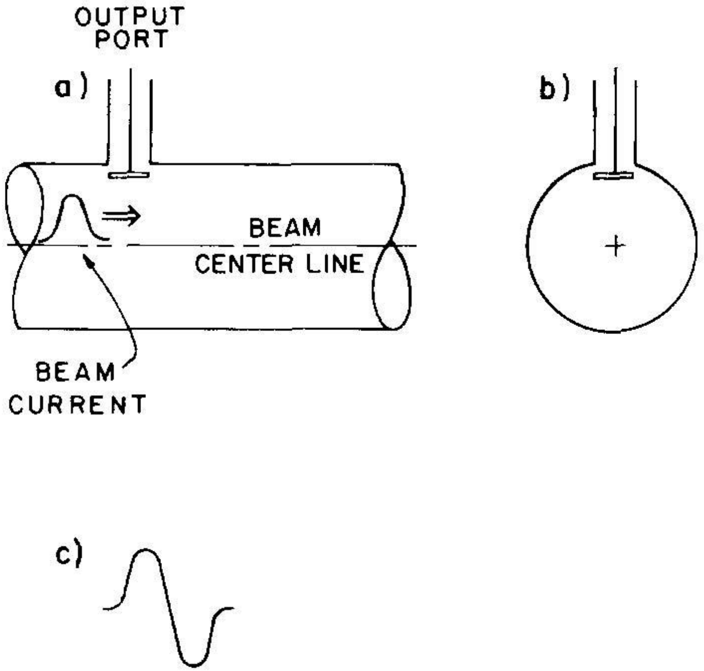
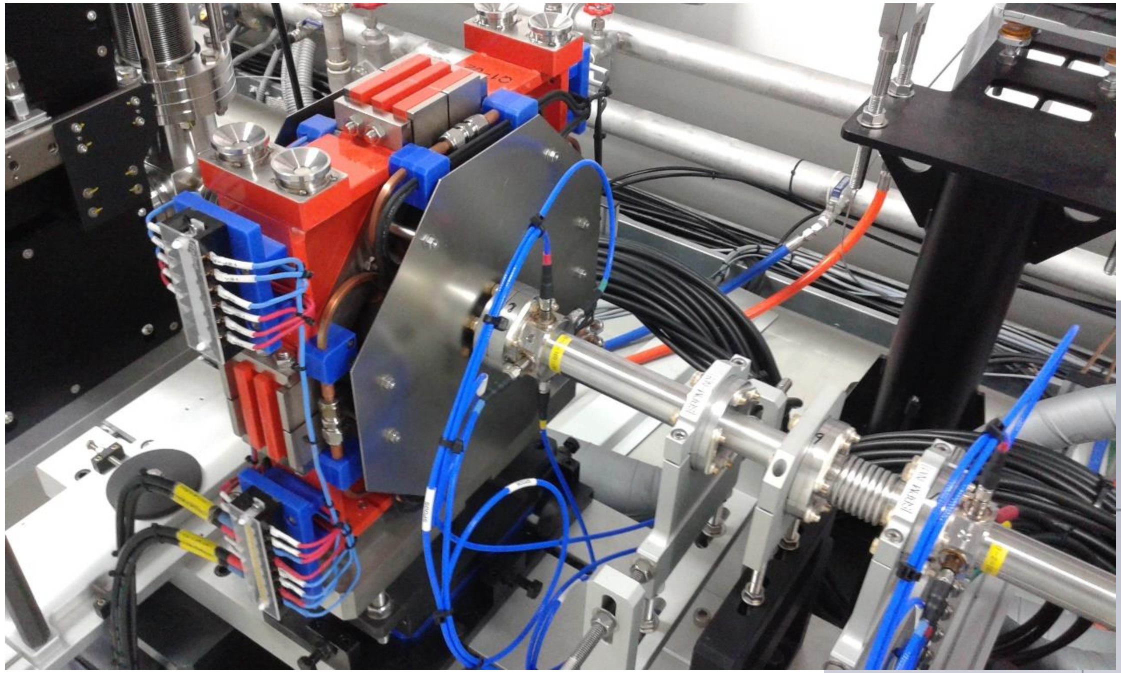
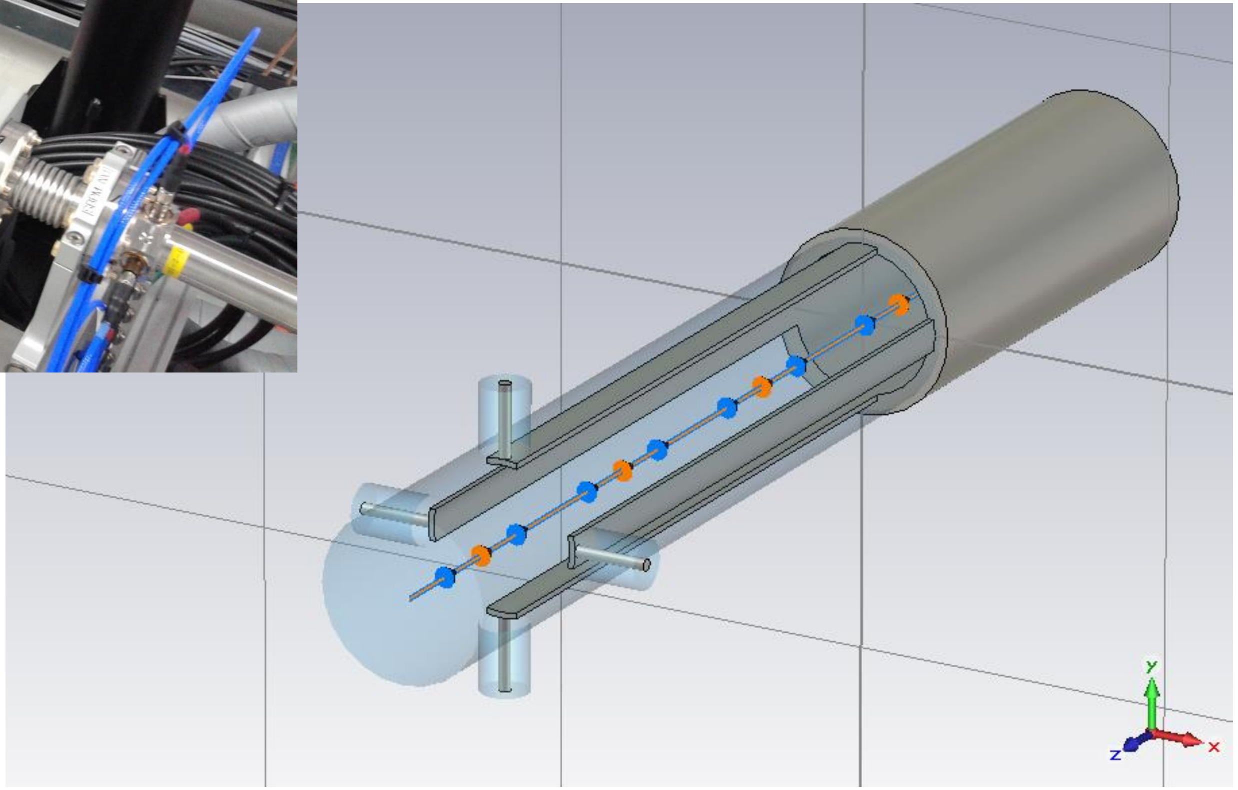


Fig. 2. Capacitive beam position monitor. (a) Side view of monitor (b) End view of monitor. (c) Induced signal on output port.

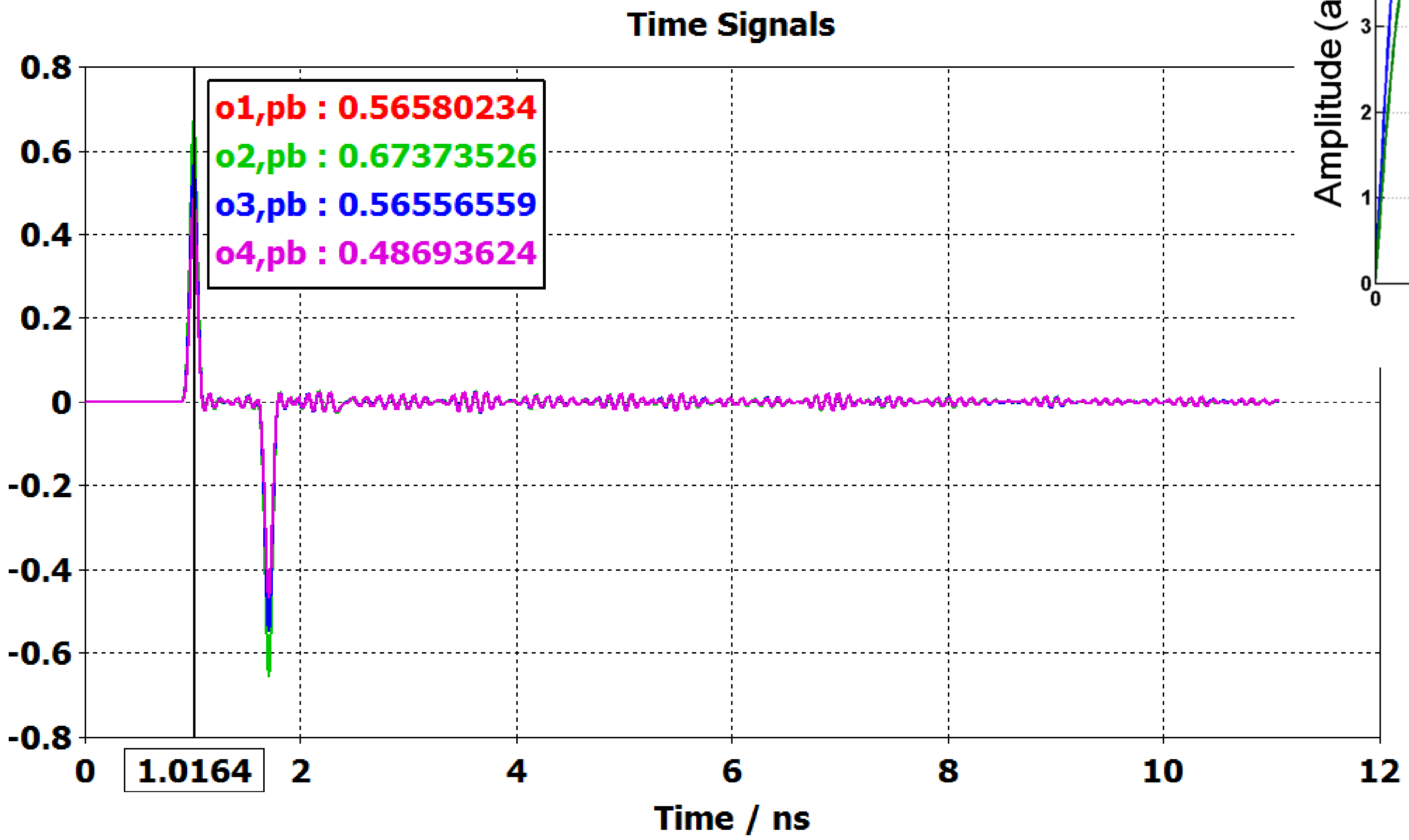
Stripline BPM for PAL-XFEL

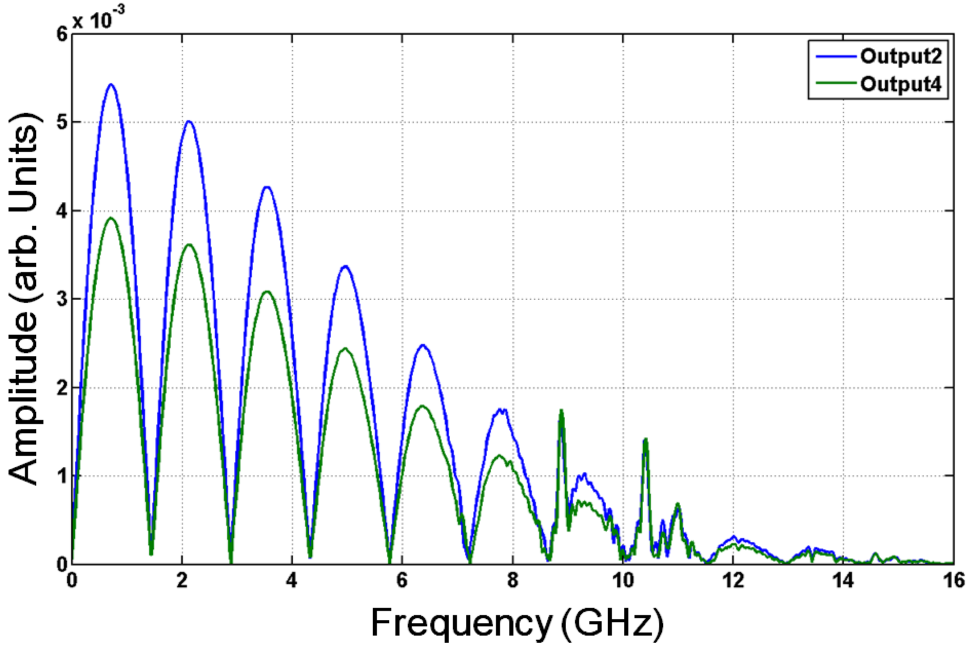




CST Simulation

Simulation Results





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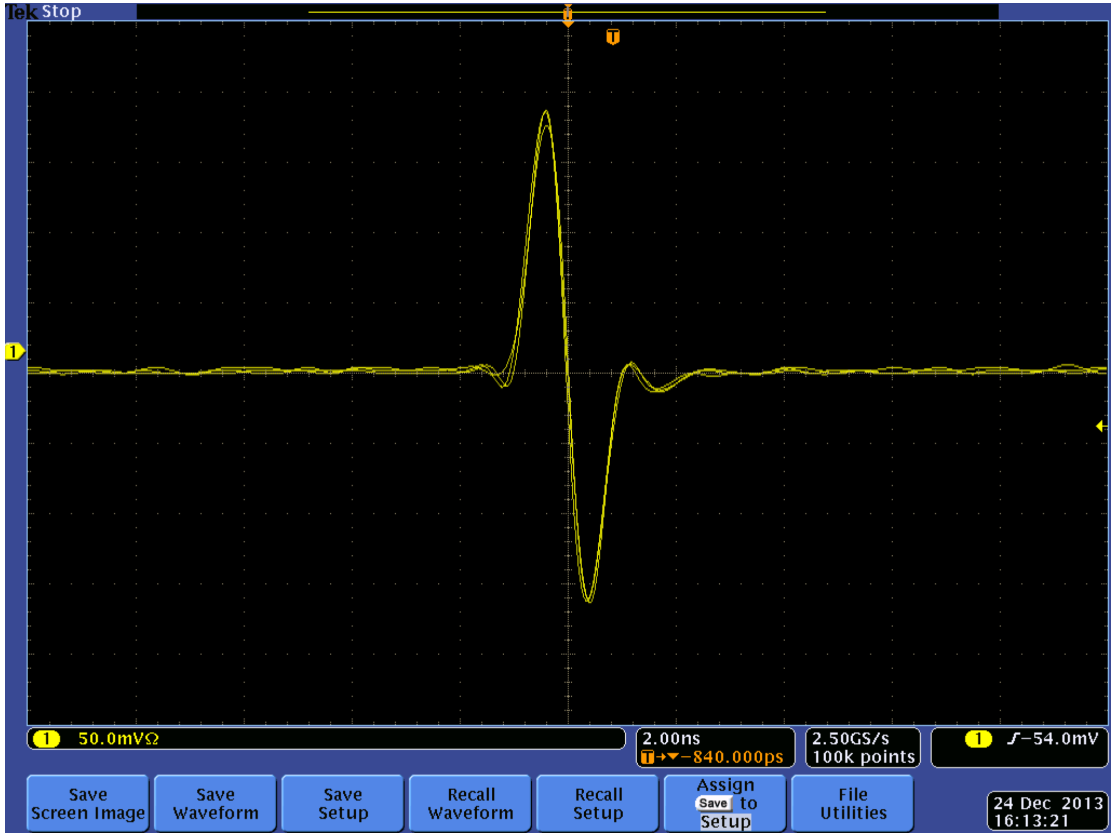
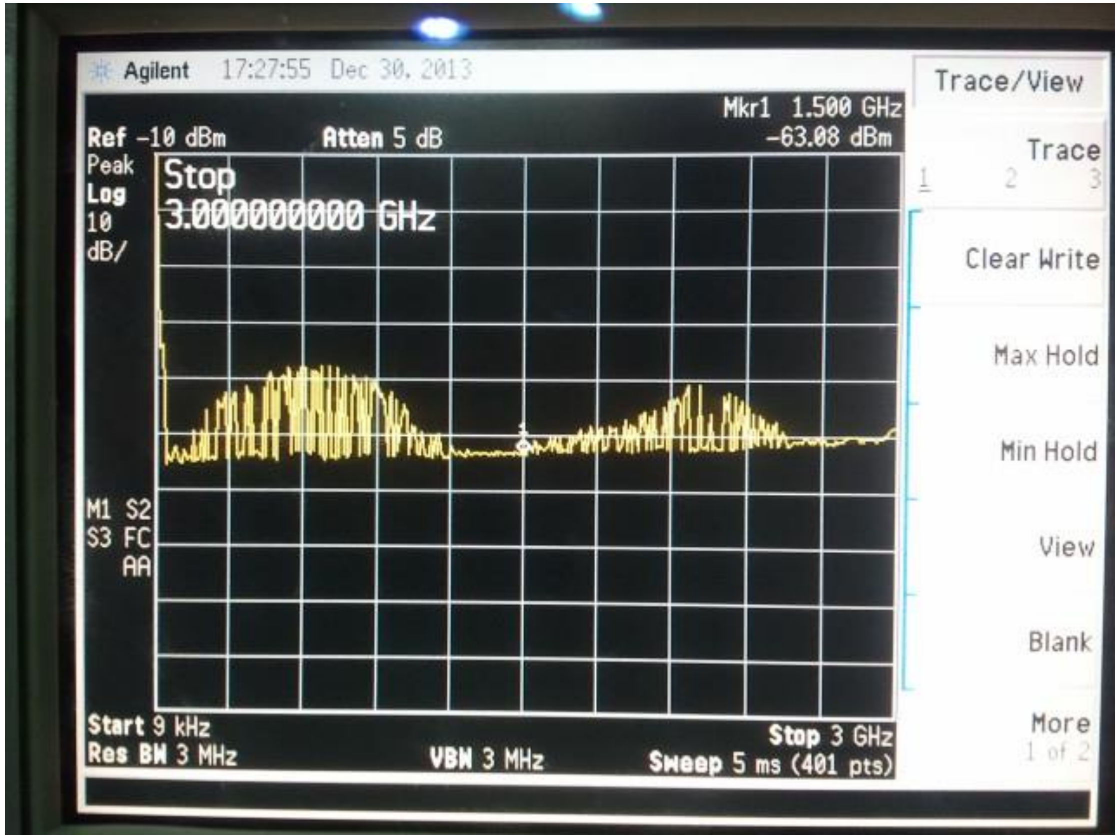
Beam Signal from Stripline

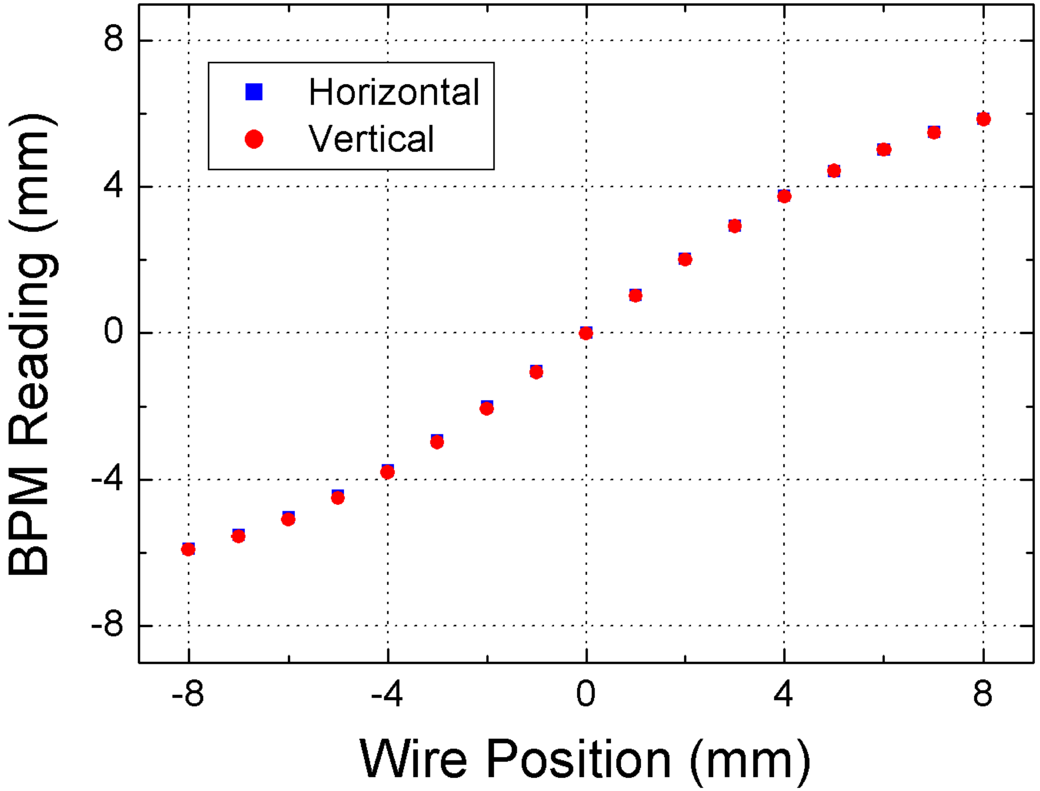


Beam Signal



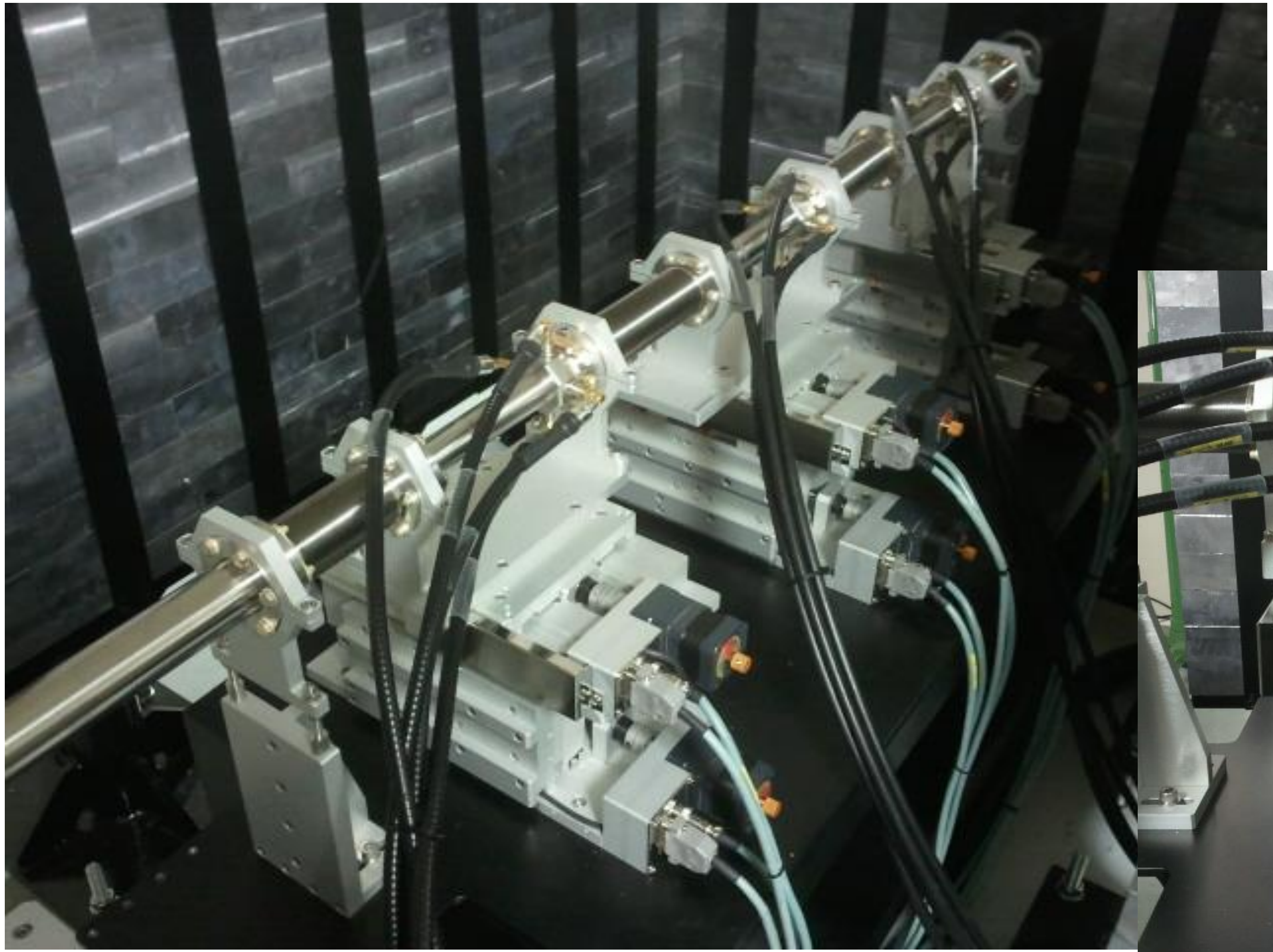
Spectrum

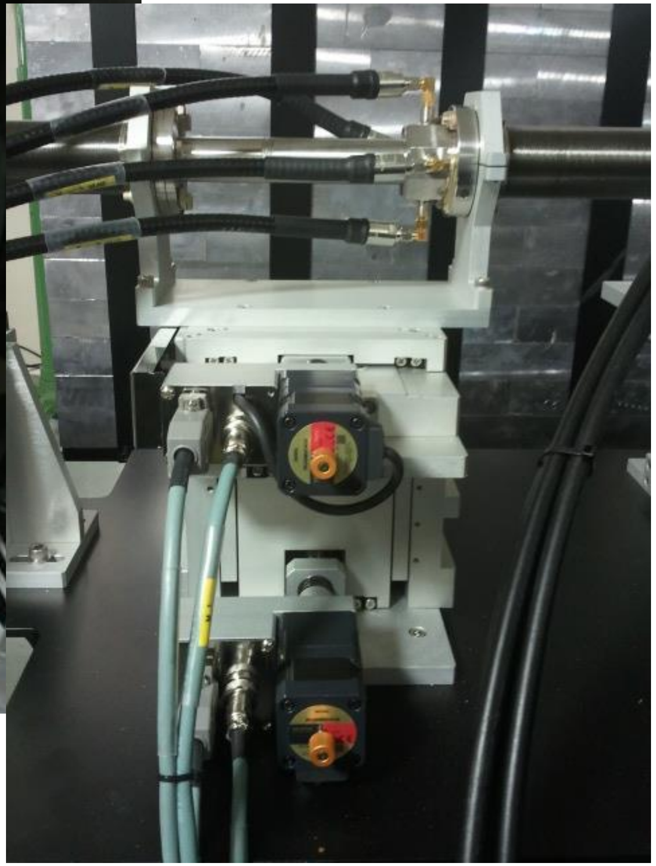
Wire Test Stand



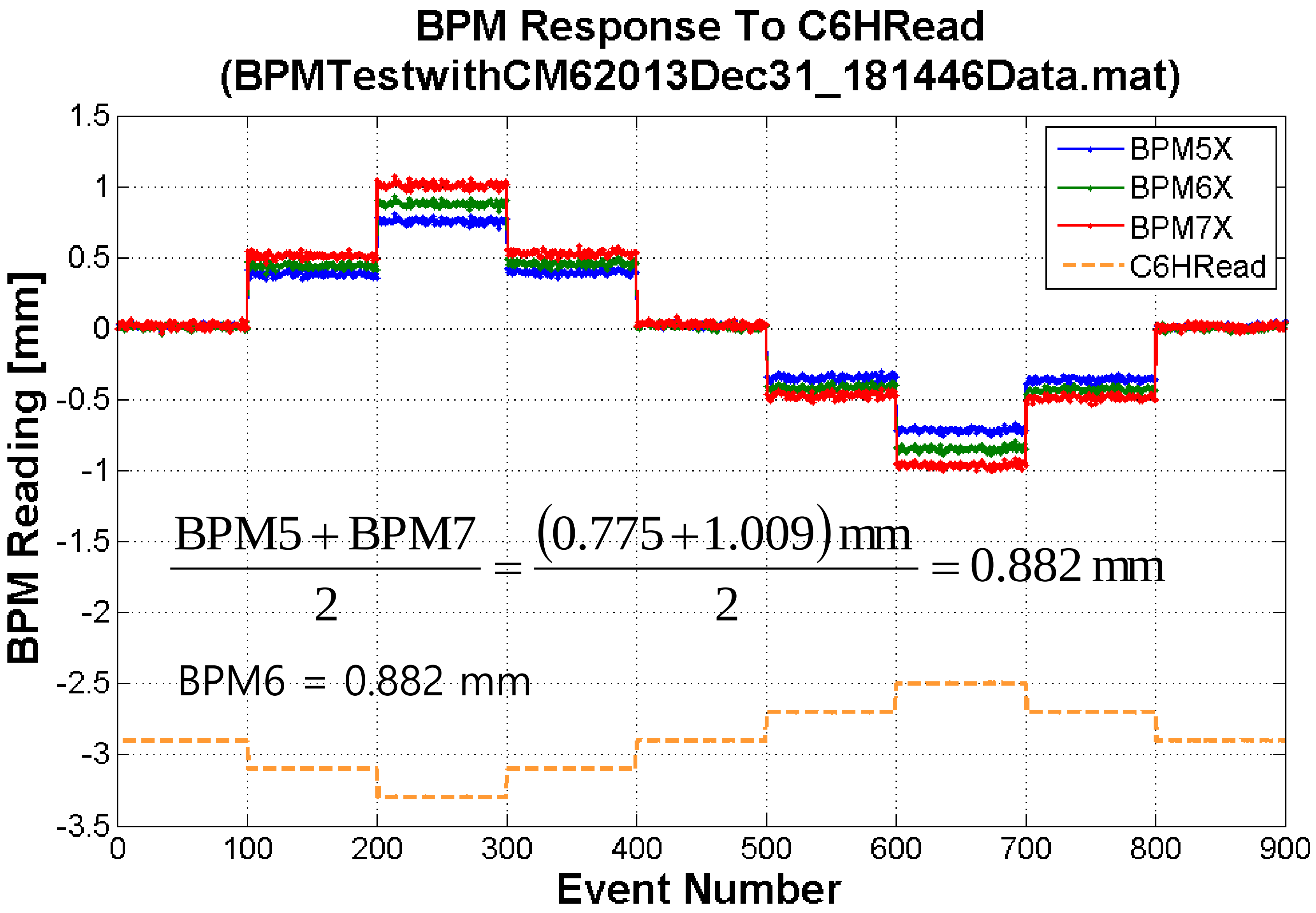
$$x = k_x \cdot \frac{R-L}{R+L} \qquad y = k_y \cdot \frac{U-D}{U+D}$$

BPM Test Stand





Corrector Current & BPMs



$$\frac{\mathrm{BPM5}+\mathrm{BPM7}}{2}=\frac{(0.775+1.009)\,\mathrm{mm}}{2}=0.882\ \mathrm{mm}$$

BPM6 = 0.882 mm

Resolution Measurement

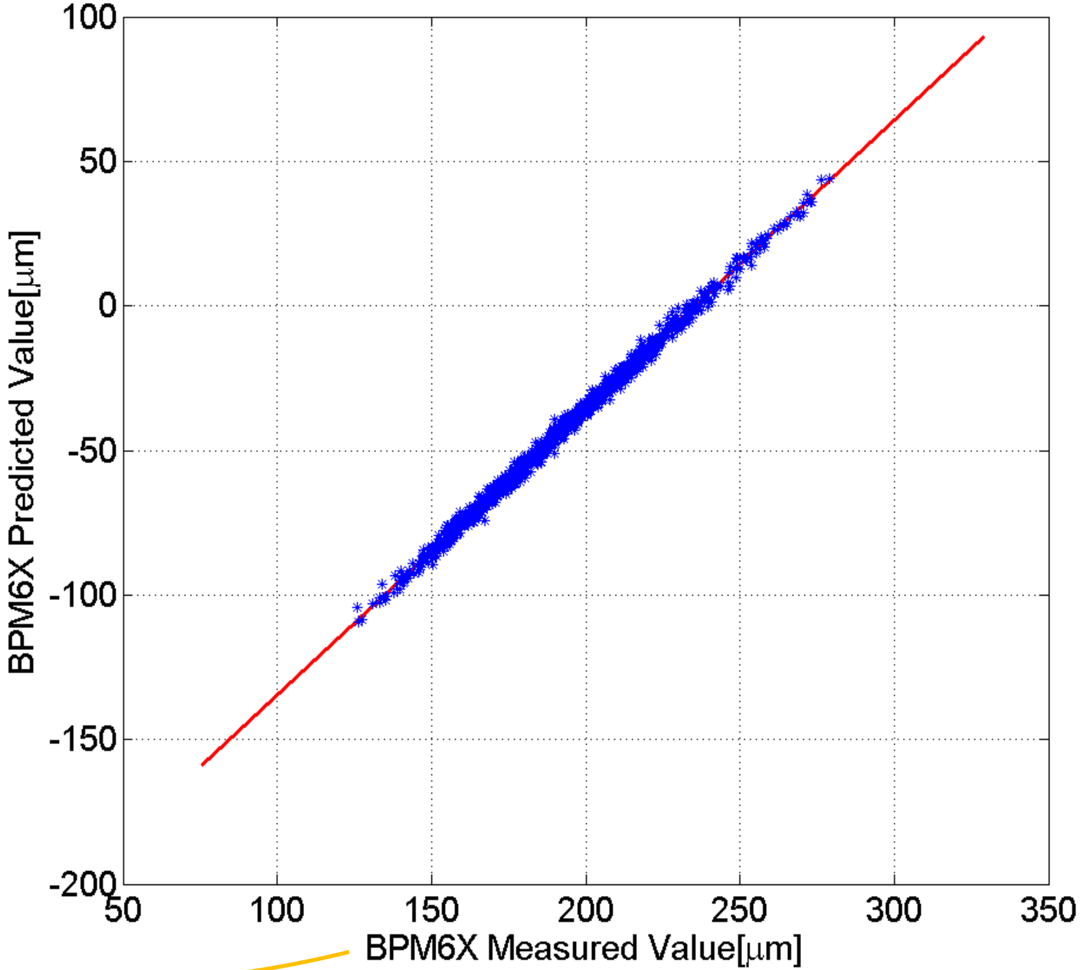
Libera Units

Libera Single Pass E (New unit)

- Sampling frequency 155 MHz
- VIRTEX 5
- Phase alignment feature
- Event receiver (EVRX)
- Measuring resolution ~ 1.2 um

www.i-tech.si

$$\text{BPM B} = \frac{\text{BPM A} + \text{BPM C}}{2}$$



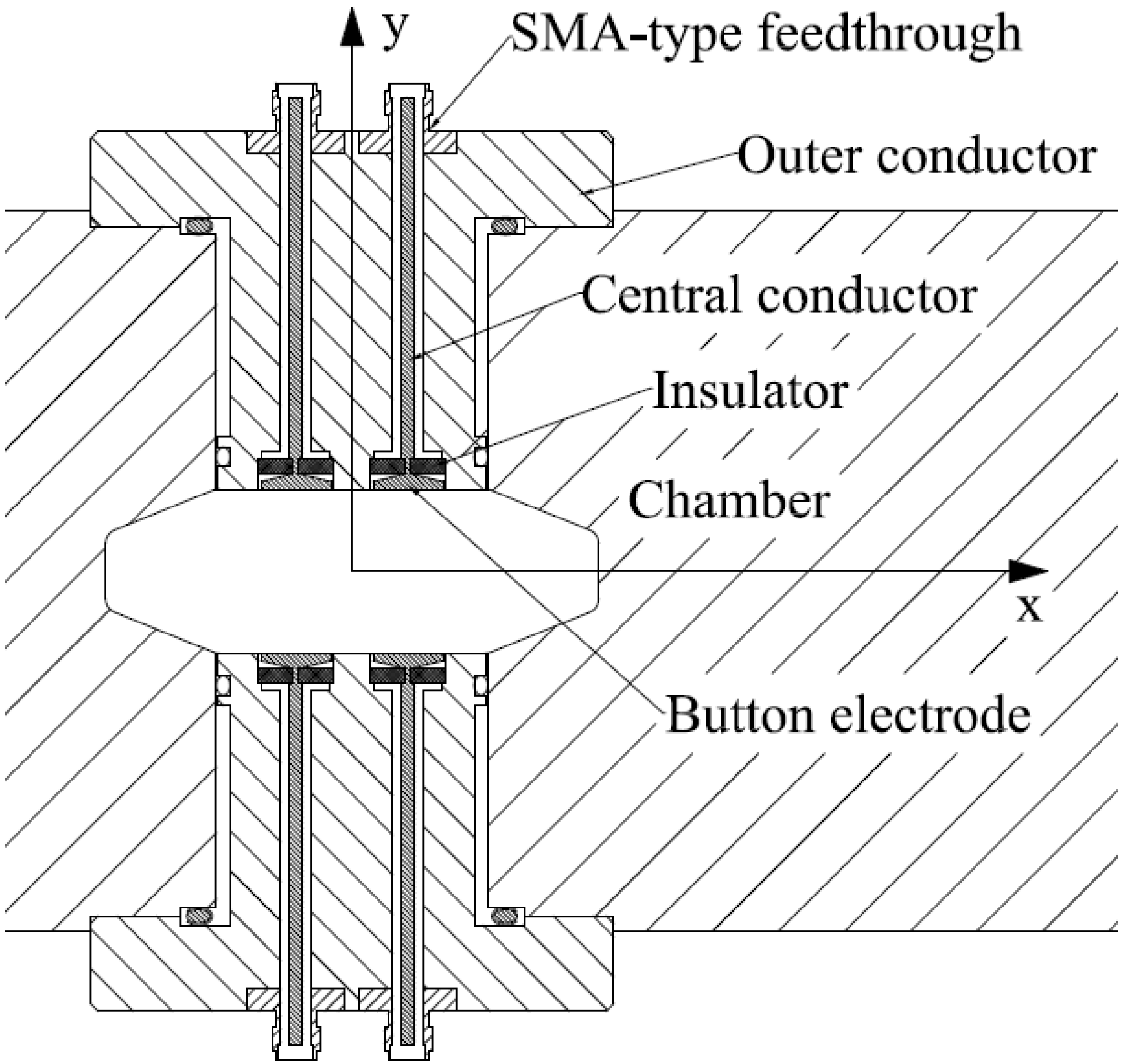
Resolution : 1.5 um @ 300 pC

Summary of Stripline BPM

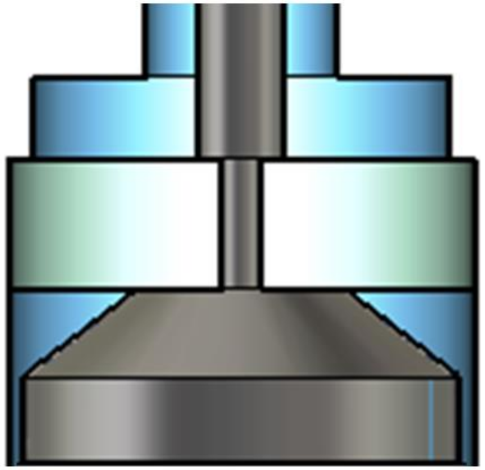
- Good linearity and low x/y coupling
- Bunch length comparable or shorter than BPM, which is some cm in length
- Can be resonant with short and open at either end, plate length a half wavelength of resonance frequency
- Used in transfer lines and low current rings

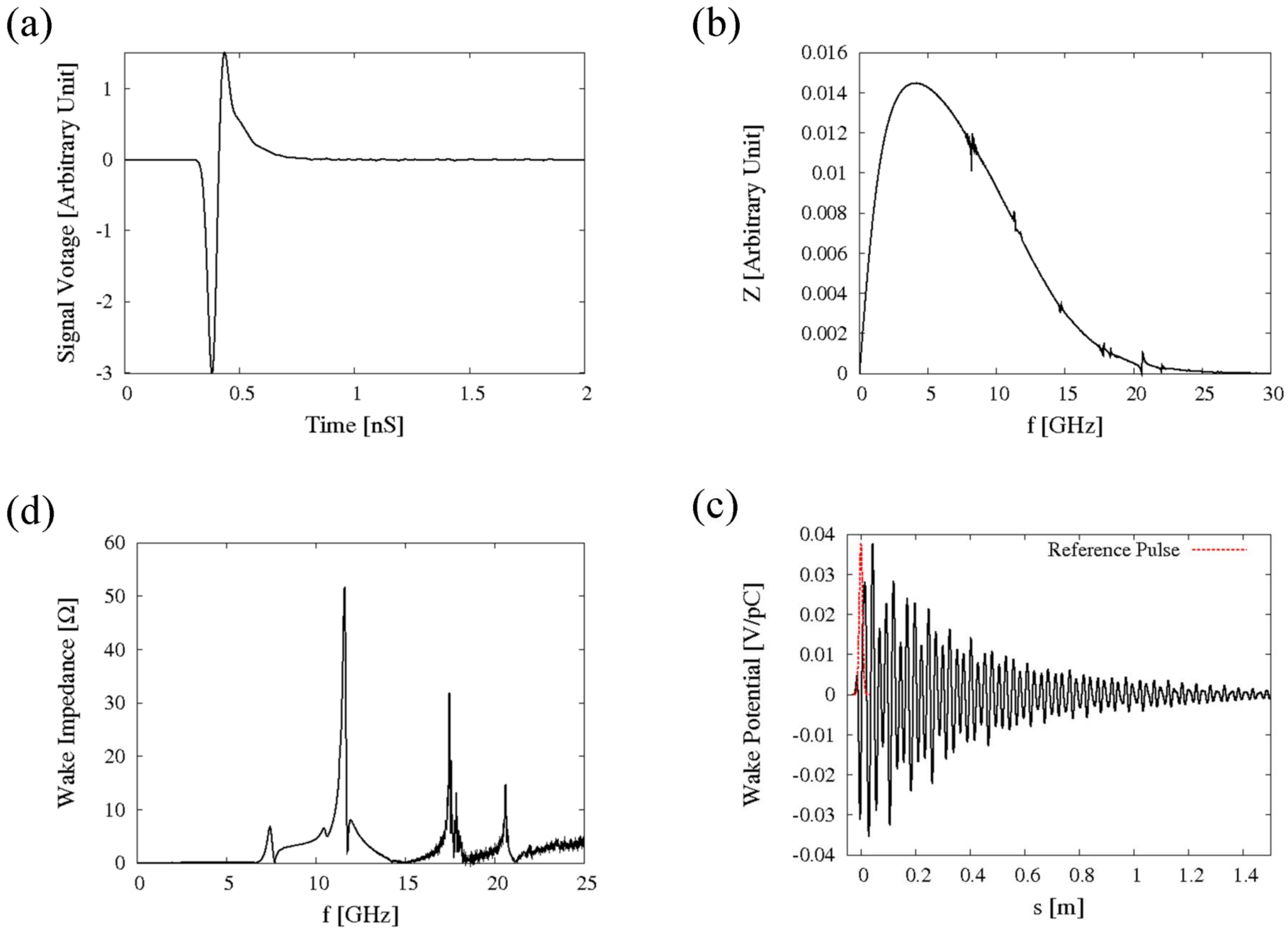
Button BPM

Button BPM of PLS-II

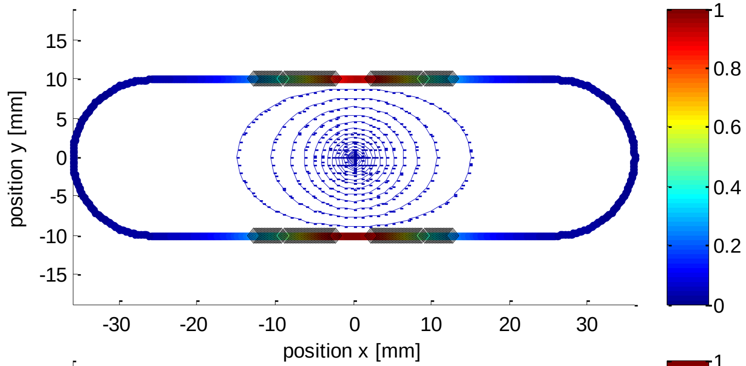


Pickup Design of Button BPM

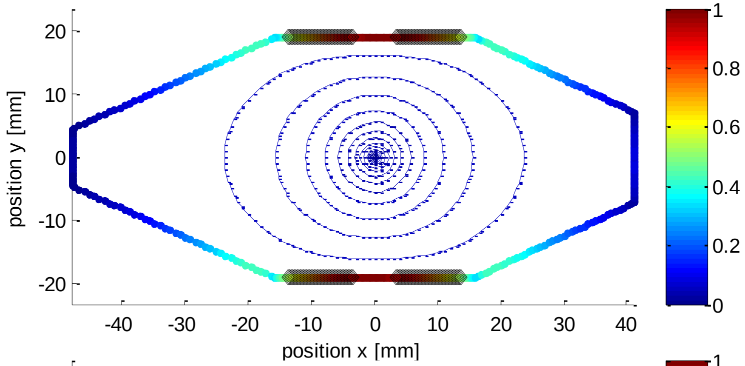


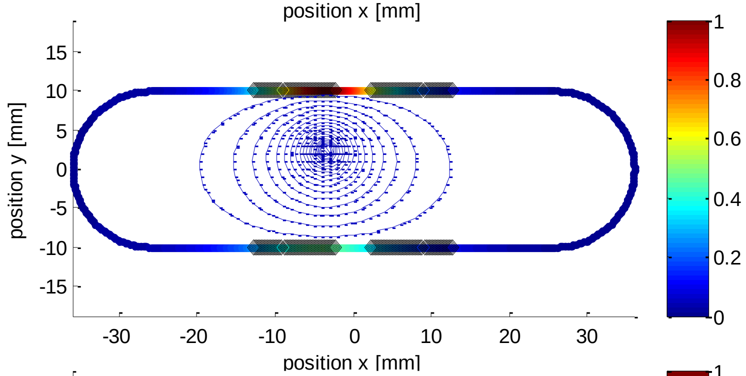


Charge Distribution in Arbitrary Cross Sections

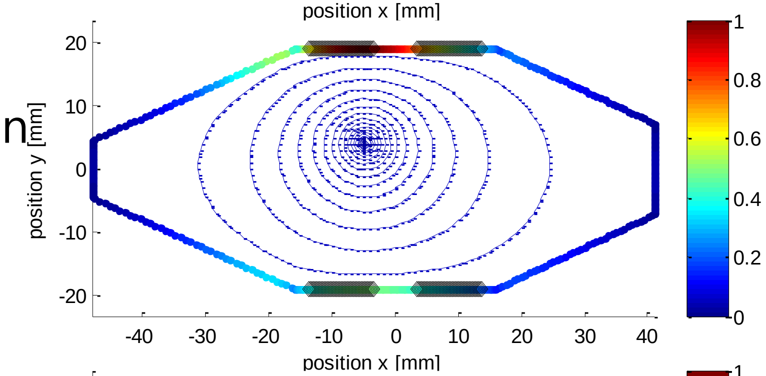


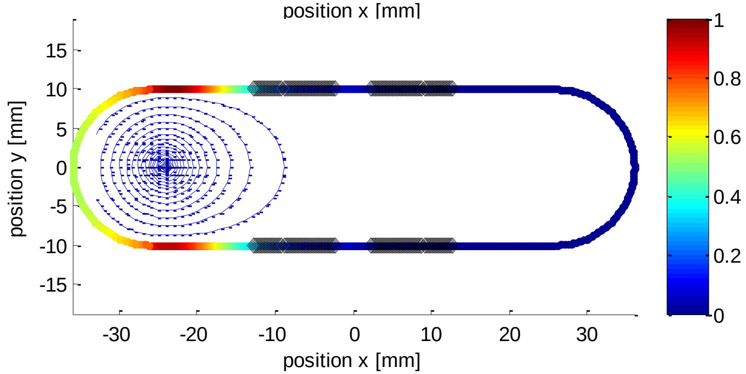
Beam centred



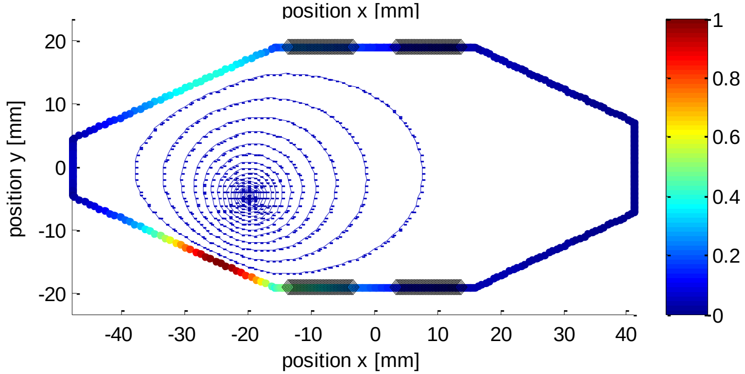


Beam position can be calculated

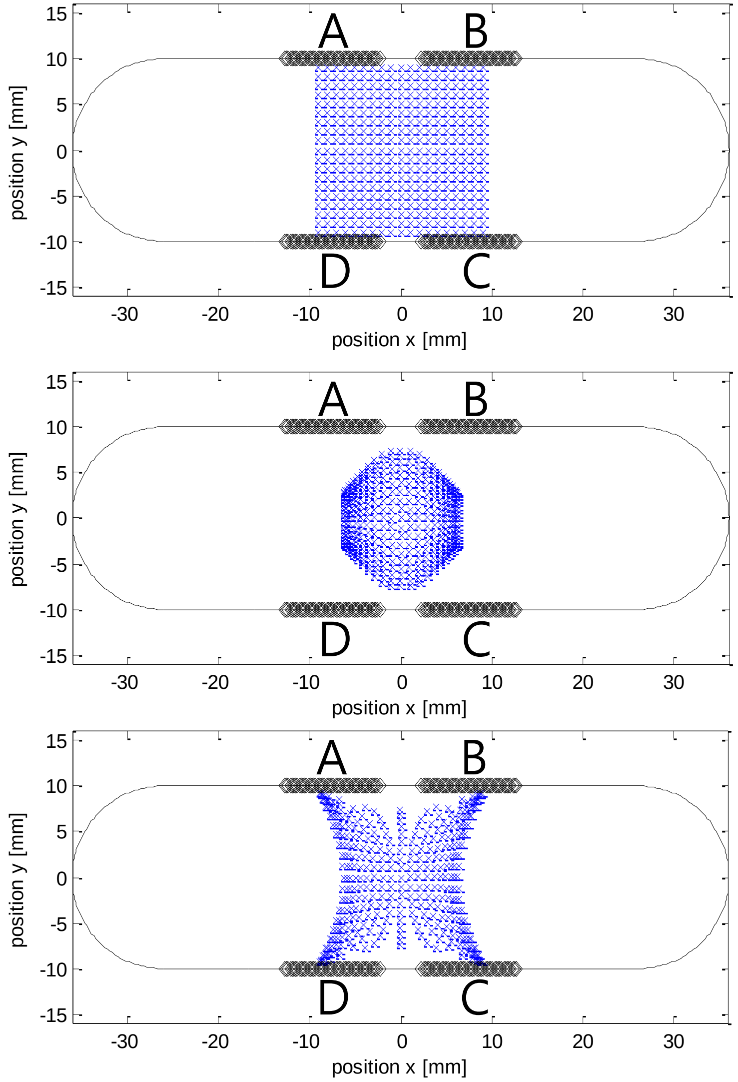




Beam position **very difficult** to calculate



Position Calculation in Arbitrary Cross Section



True Beam Position

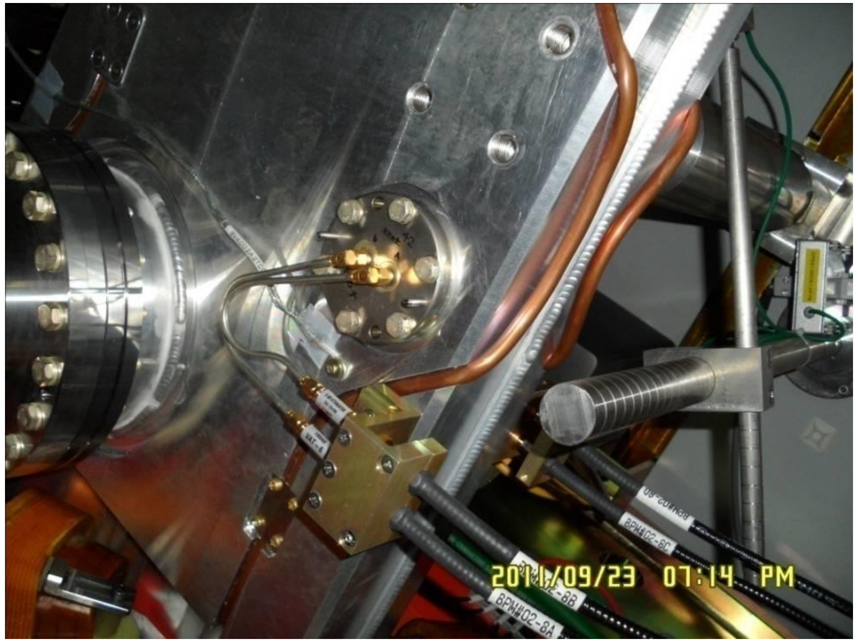
$$x = k_x \cdot \left(\frac{B-A}{B+A} + \frac{C-D}{C+D} \right)$$

$$y = k_y \cdot \left(\frac{B-C}{B+C} + \frac{A-D}{A+D} \right)$$

$$x = k_x \cdot \frac{(B+C)-(A+D)}{A+B+C+D}$$

$$y = k_y \cdot \frac{(B+A)-(C+D)}{A+B+C+D}$$

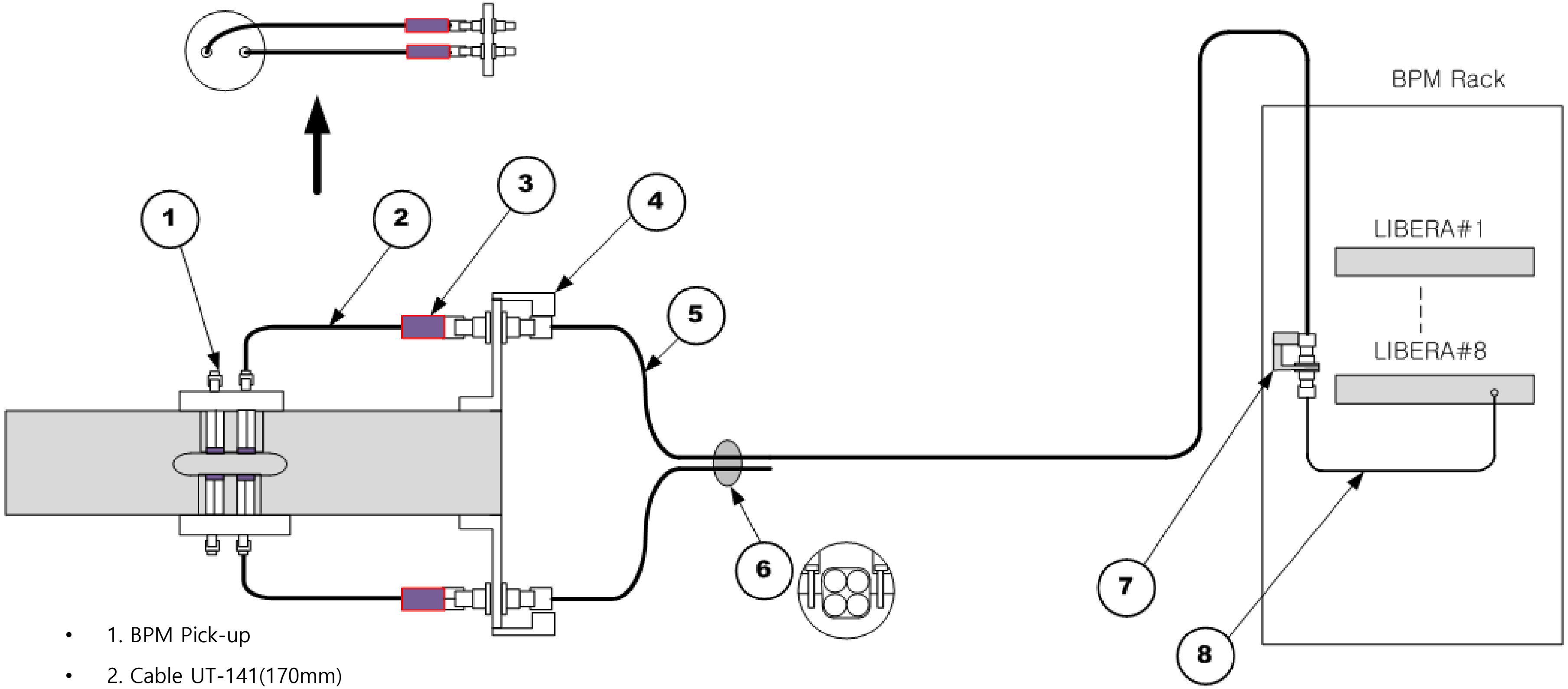
BPM of PLS-II Storage Ring



Flange Type BPM Pickup

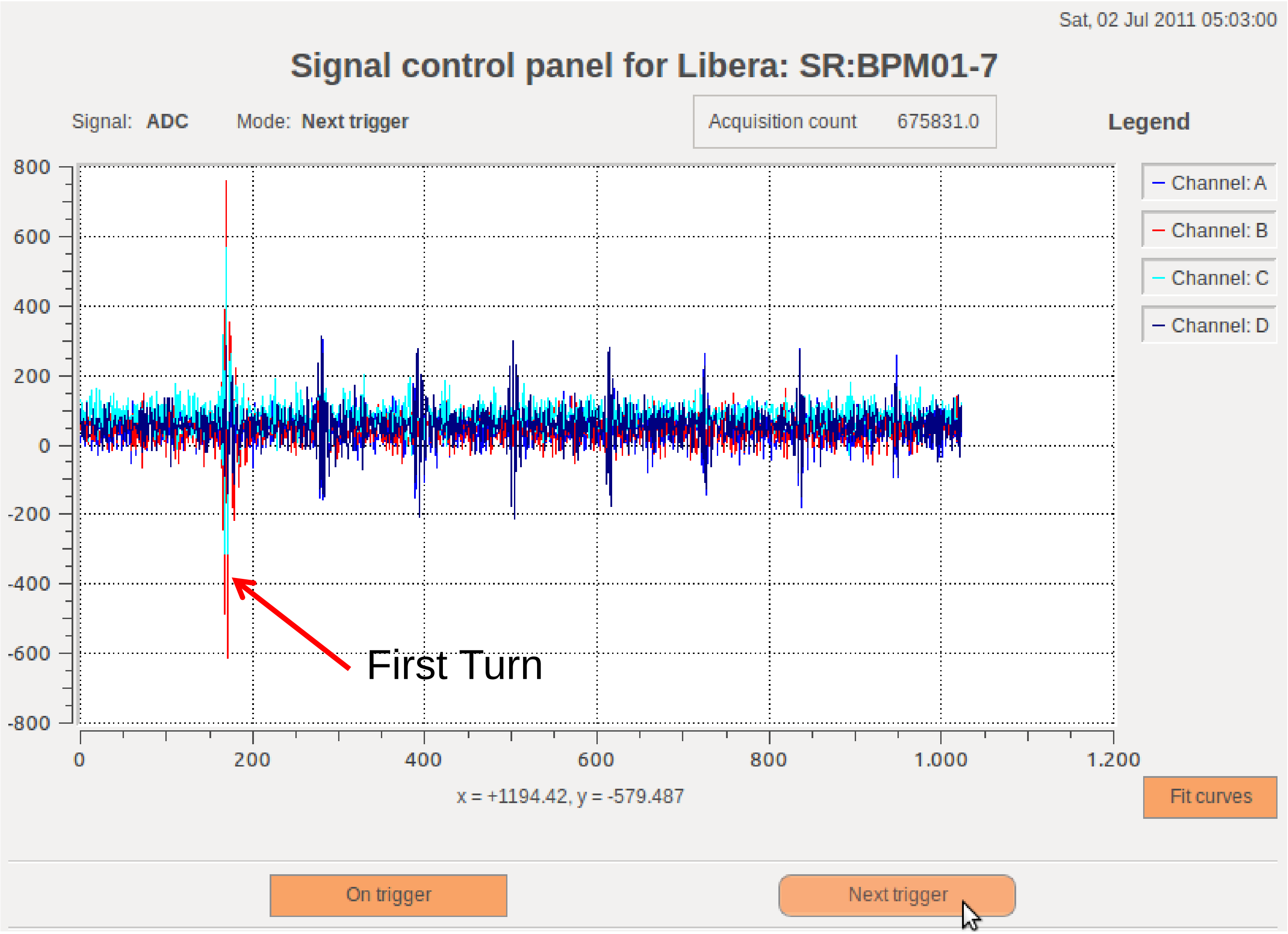
Racetrack Type BPM Pickup

Cable Connection of BPM



- 1. BPM Pick-up
- 2. Cable UT-141(170mm)
- 3. Attenuator(6db)
- 4. Bracket1
- 5. Andrew LDF4-50A 1/4"
- 6. Bracket2
- 7. Bracket3
- 8. Cable SF402(2m)

Data of Turn by Turn Data

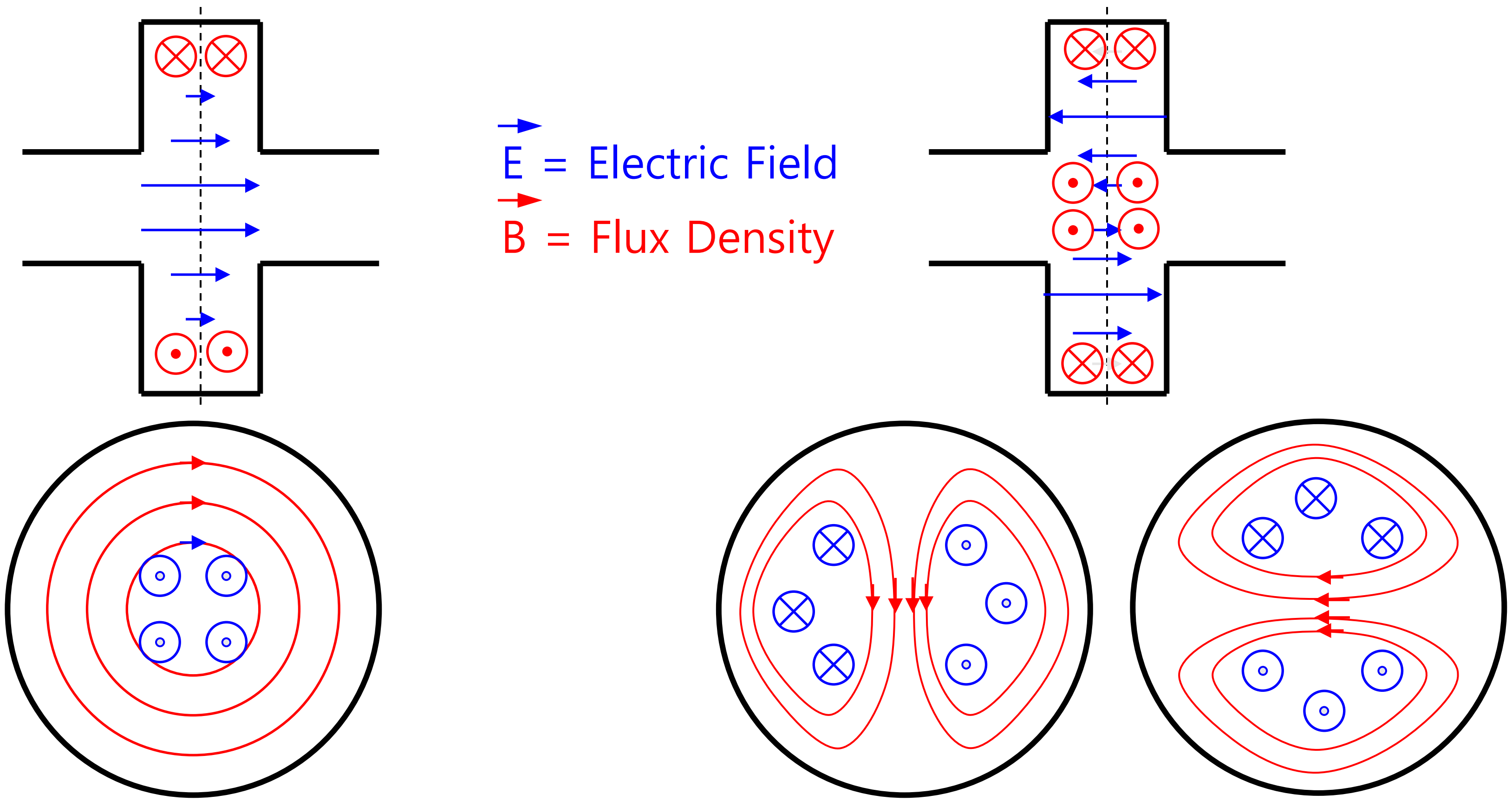


Turn by Turn BPM Data

Summary of Button BPM

- Poor linearity and significant x/y coupling (without numerical linearization)
- Bunch length comparable or shorter than BPM, which is about 1 cm diameter
- Bandwidth 100 MHz~5 GHz
- Used in high energy machines, synchrotron light sources

Cavity BPM



Monopole Mode TM_{010}
Lower Resonance Frequency
Excited by on and off centre beam

Dipole Mode TM_{110}
Higher Resonance Frequency
Excited only by off centre beam

Output Voltage from Cavities

- **E-field for TM_{010} mode and TM_{110} mode**
  - TM_{010} mode

$$E_z = CJ_0\left(\frac{j_{01}r}{R}\right)e^{i\omega_{010}t}$$

  - TM_{110} mode

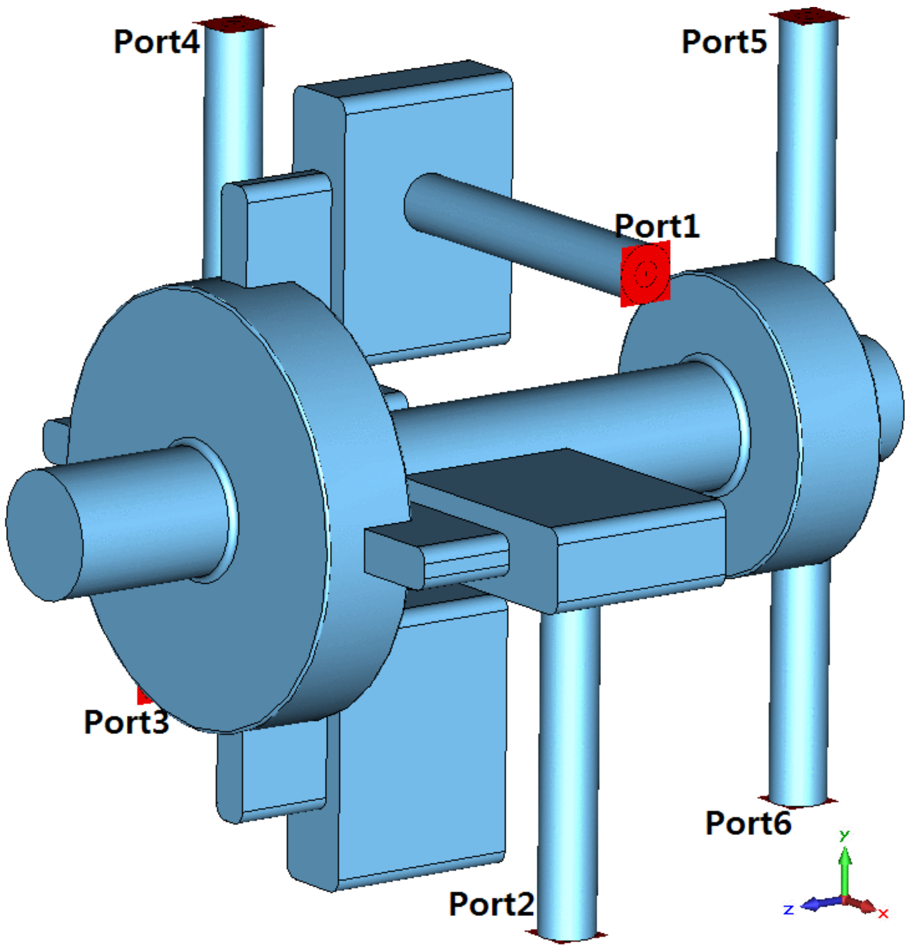
$$E_z = CJ_1\left(\frac{j_{11}r}{R}\right)cos\phi \cdot e^{i\omega_{110}t}$$

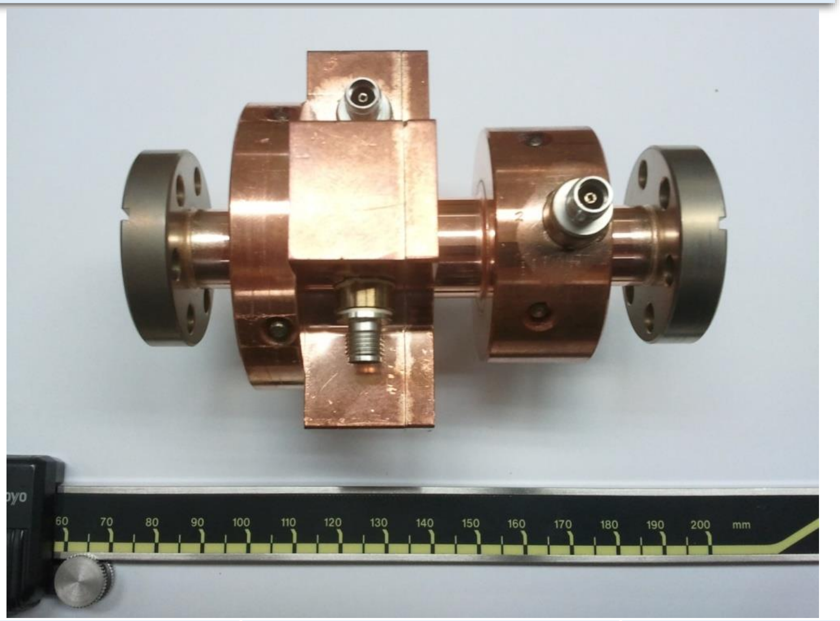
- **Output signal induced by TM_{010} mode and TM_{110} for impedance Z**
  - Using the definition of normalized shunt impedance, R/Q, and approximation of Bessel function, $J_n(x) \cong \frac{1}{n!}\left(\frac{x}{2}\right)^n$

→ Signal induced by TM_{010} mode: $V_{010} = \frac{1}{2}q\omega\sqrt{\frac{Z}{Q_{ext}}(R/Q)}$

→ Signal induced by TM_{110} mode: $V_{110} = \frac{1}{2}q\omega\sqrt{\frac{Z}{Q_{ext}}(R/Q)_0(\frac{\delta x}{x_0})^2}$

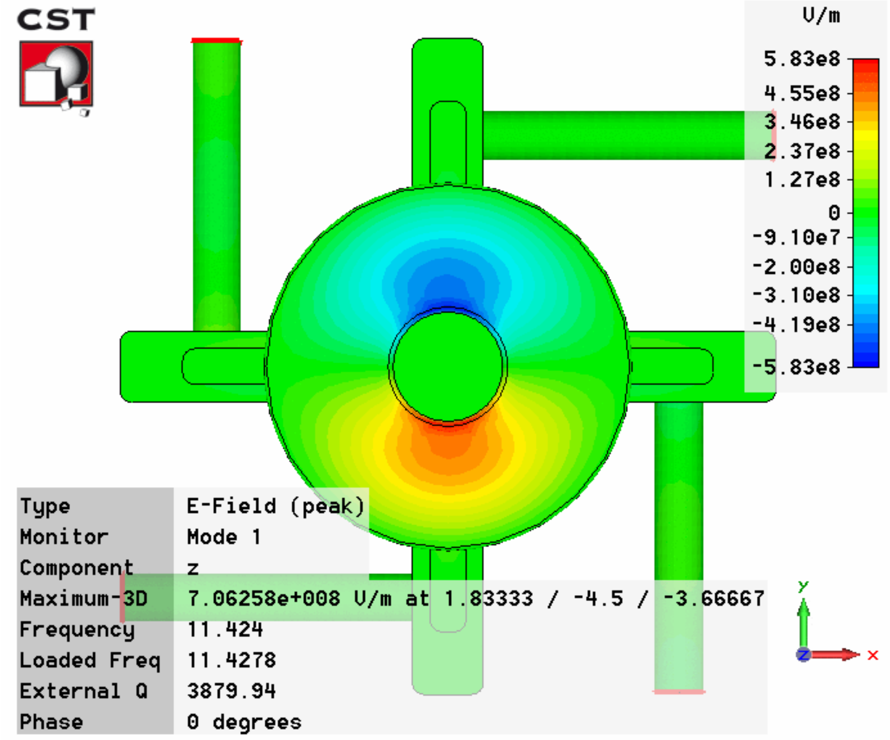
X-Band Cavity BPM

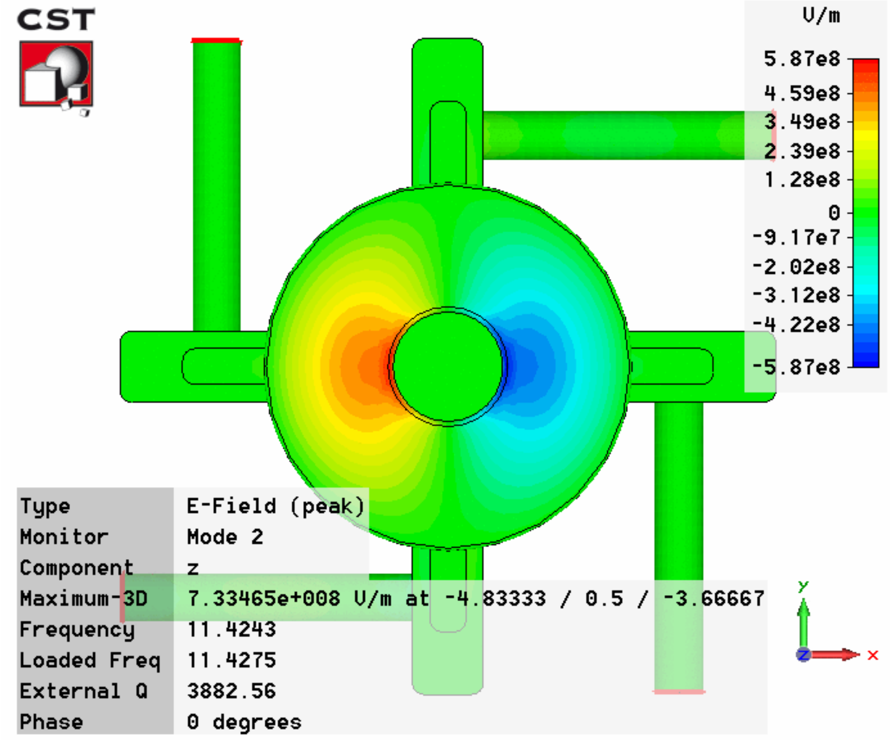


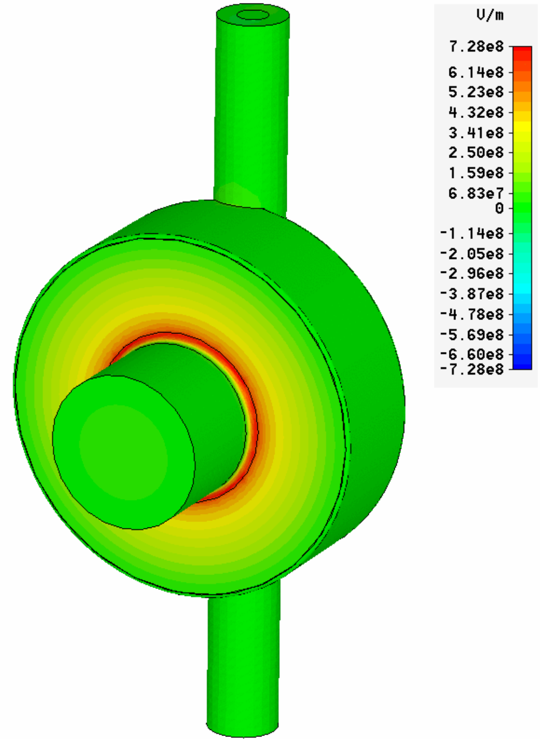


Parameters	XY Cavity (Dipole Cavity)	Reference Cavity (Monopole Cavity)
Mode	TM110	TM010
Frequency	11.424 GHz	11.424 GHz
Loaded Q Factor	2000 – 3000	2000 – 3000
R/Q	> 2 Ohms/mm	> 12 Ohms
Induced Voltage	> 5 mV/pC·mm	> 20 mV/pC
X/Y Cross Talk Level	< -20 dB	-

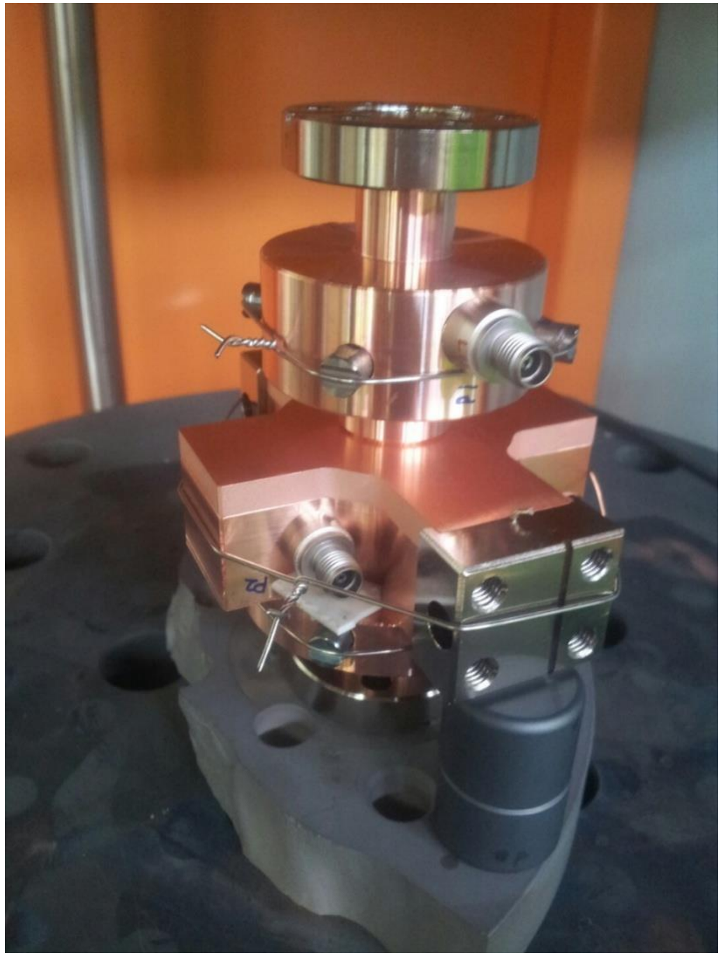
CST Simulation Results



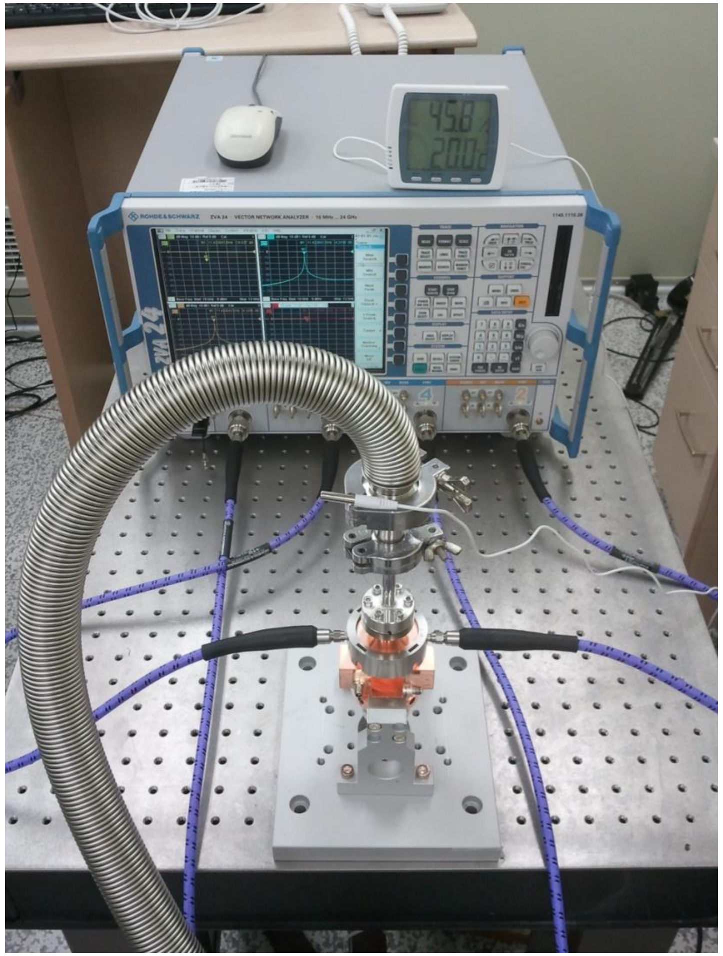




Brazing & Tuning

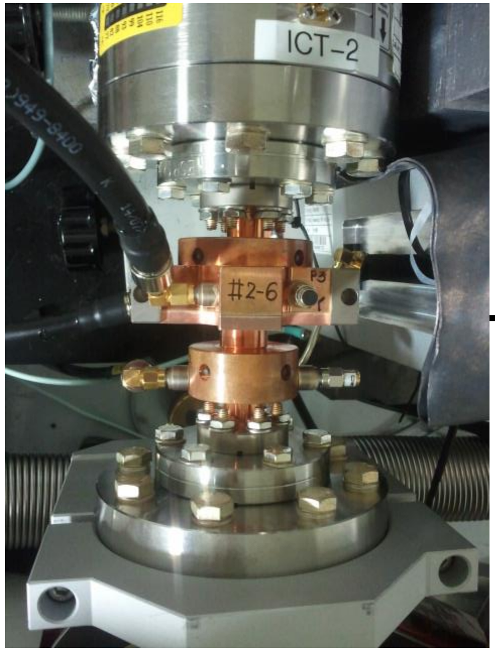


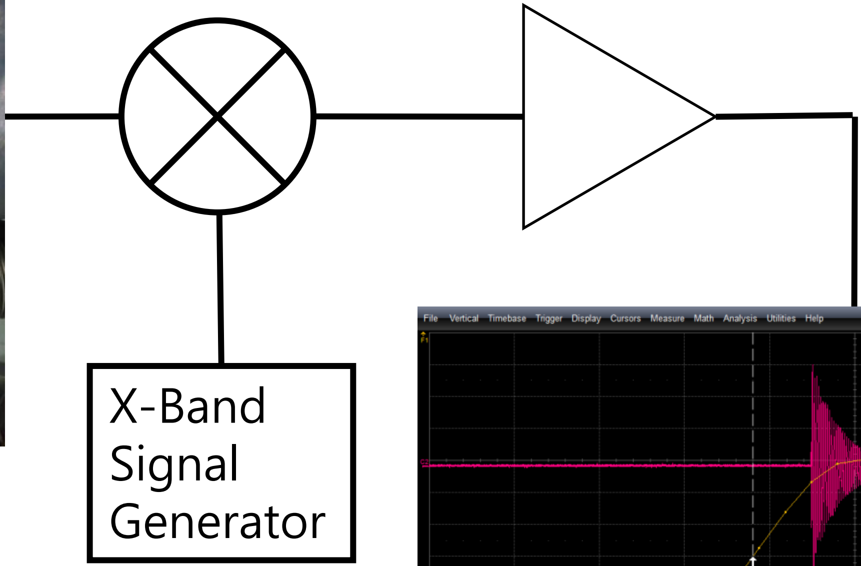
Brazing



Cavity BPM Tuning

Beam Test Result

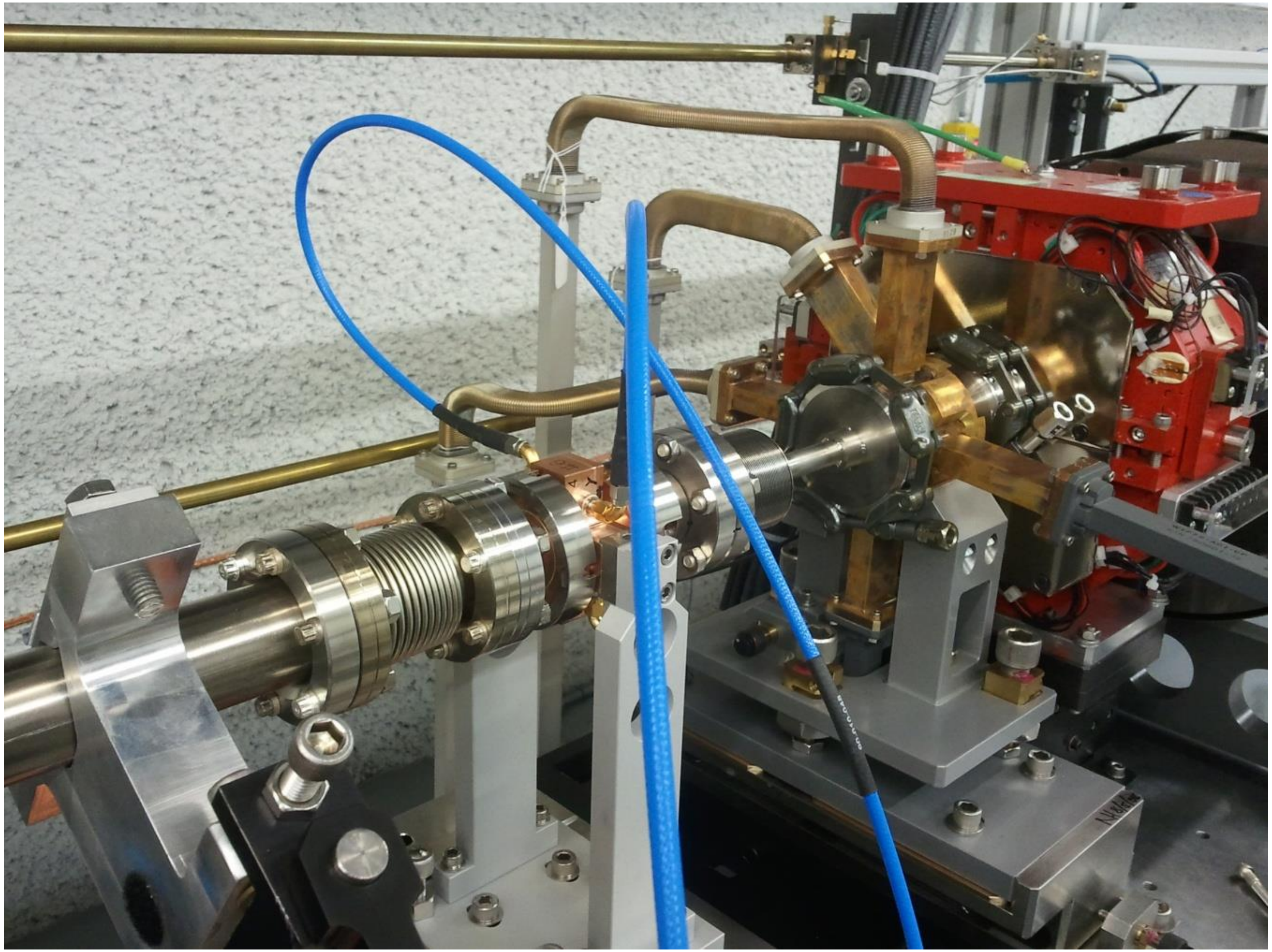




IF Signal

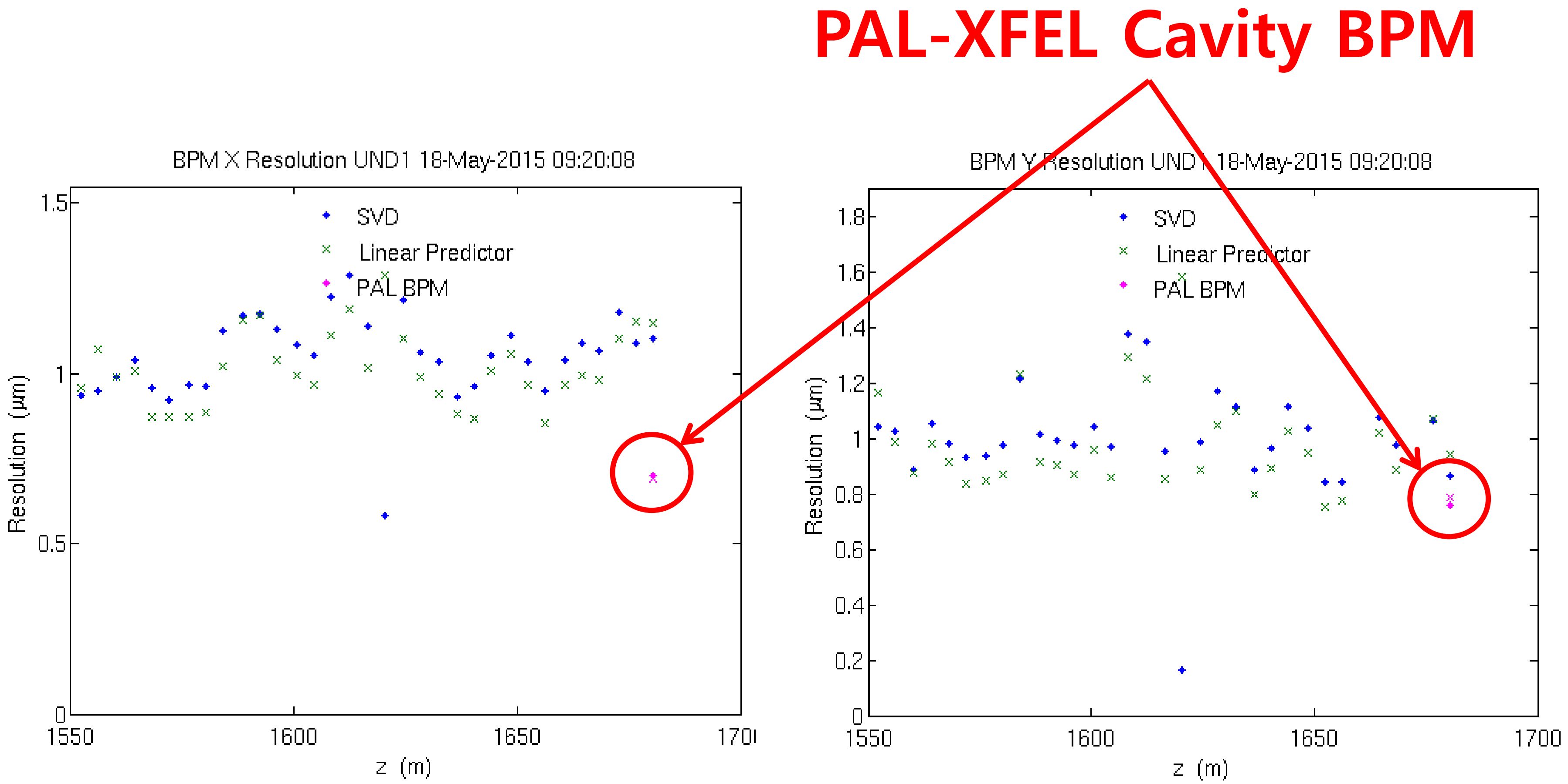
Signal Voltage (Peak) = 0.7 V
Signal Power = 0.7^2 / 50 Ohm
= 9.8 mW = 10 dBm

Beam Test at LCLS



Test Result of Cavity BPM Resolution at LCLS

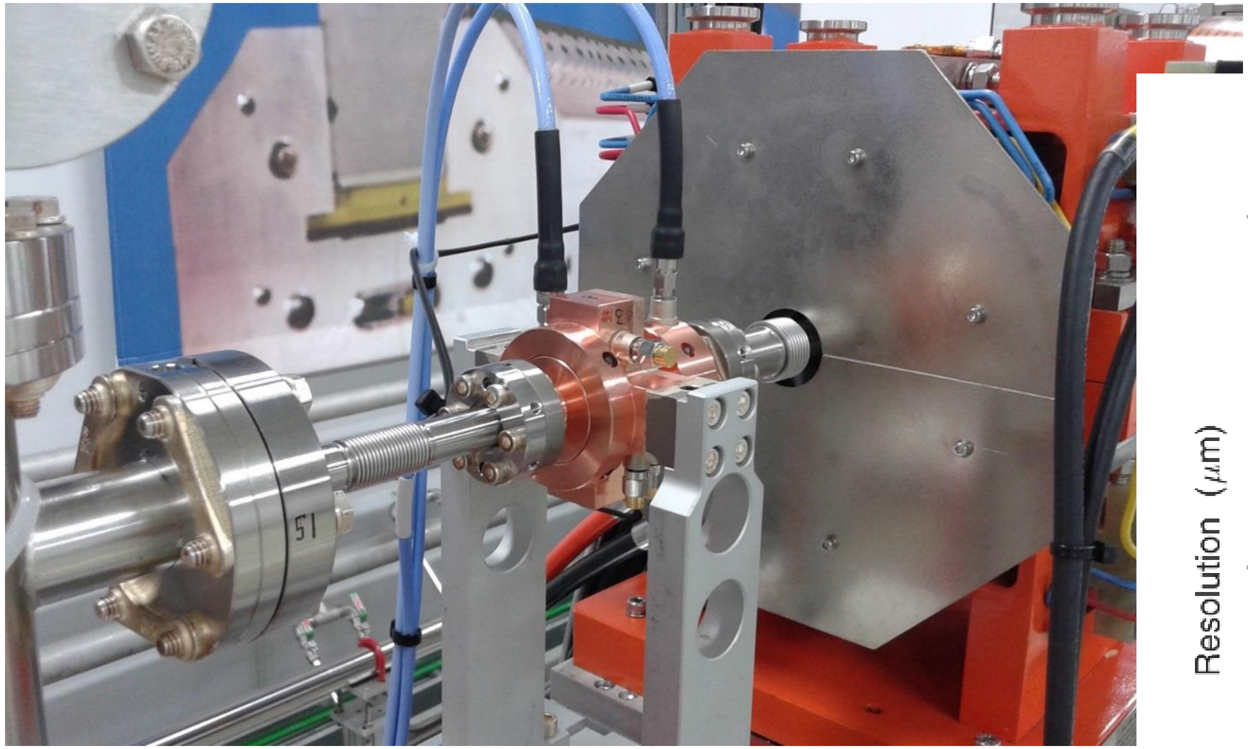
- Measured Resolution: 700 nm (x), 800 nm (y)

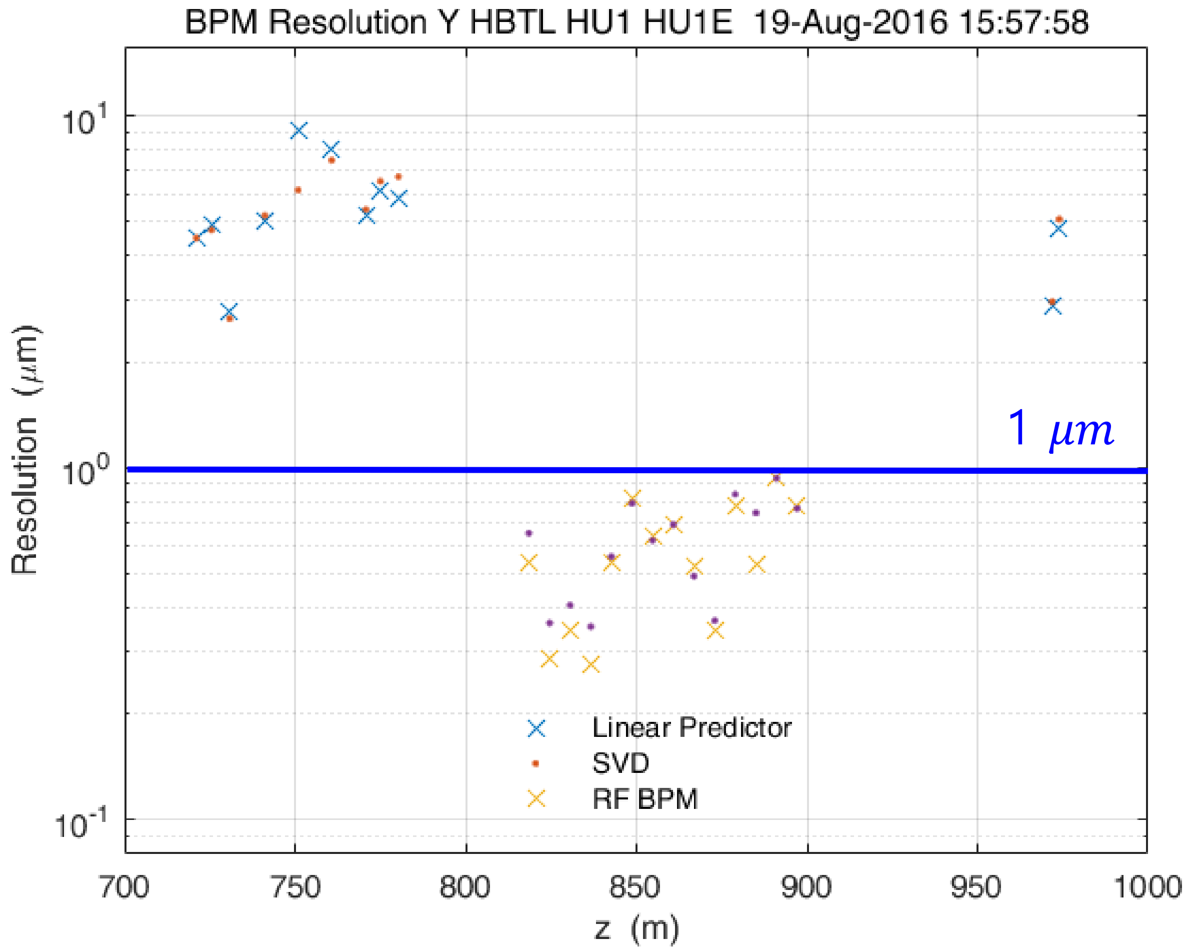


Data at 25 pC, 5 dB Att, 10 dB Ref Att

미래기반 가속기
전문인력양성 사업단

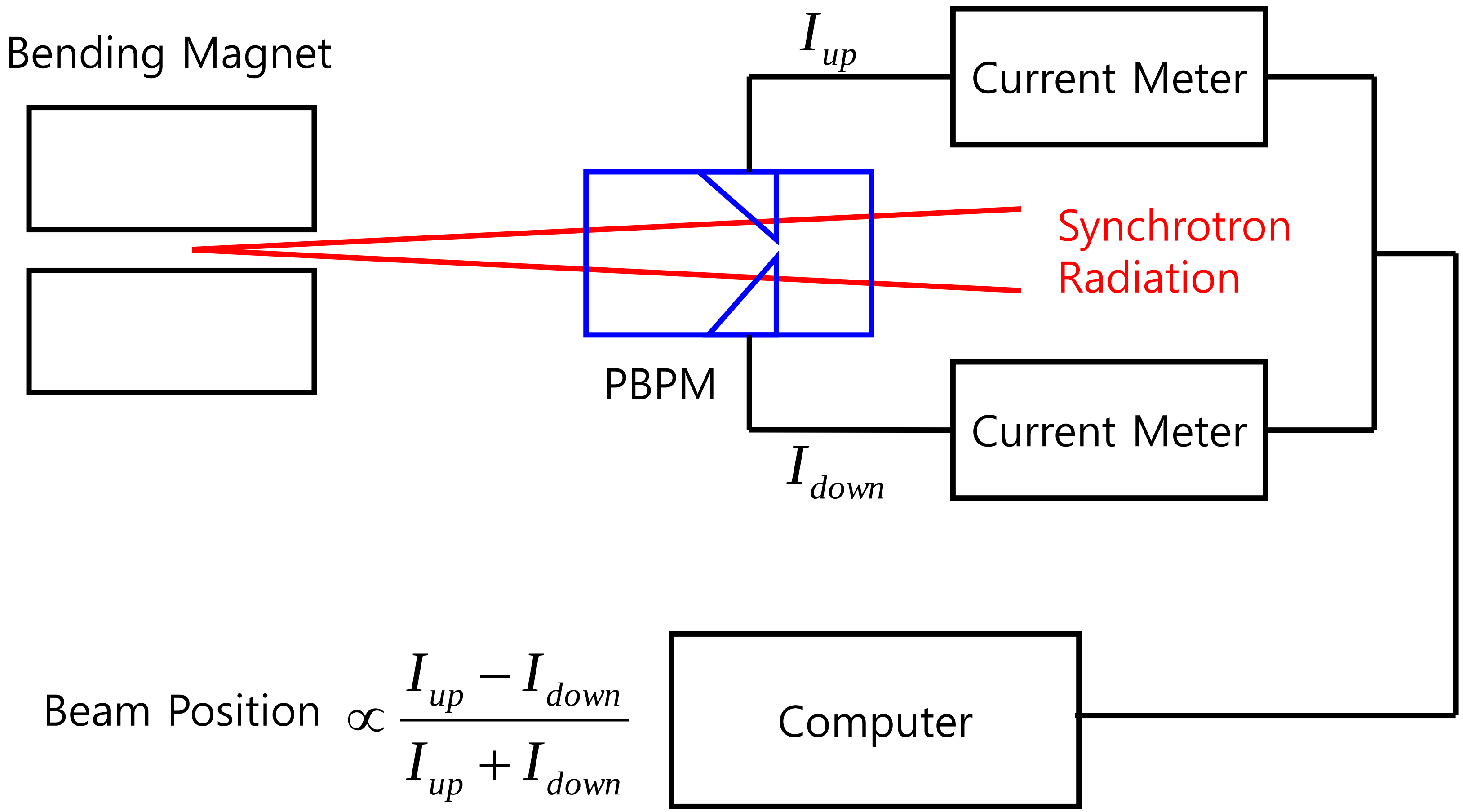
PAL-XFEL Cavity BPM





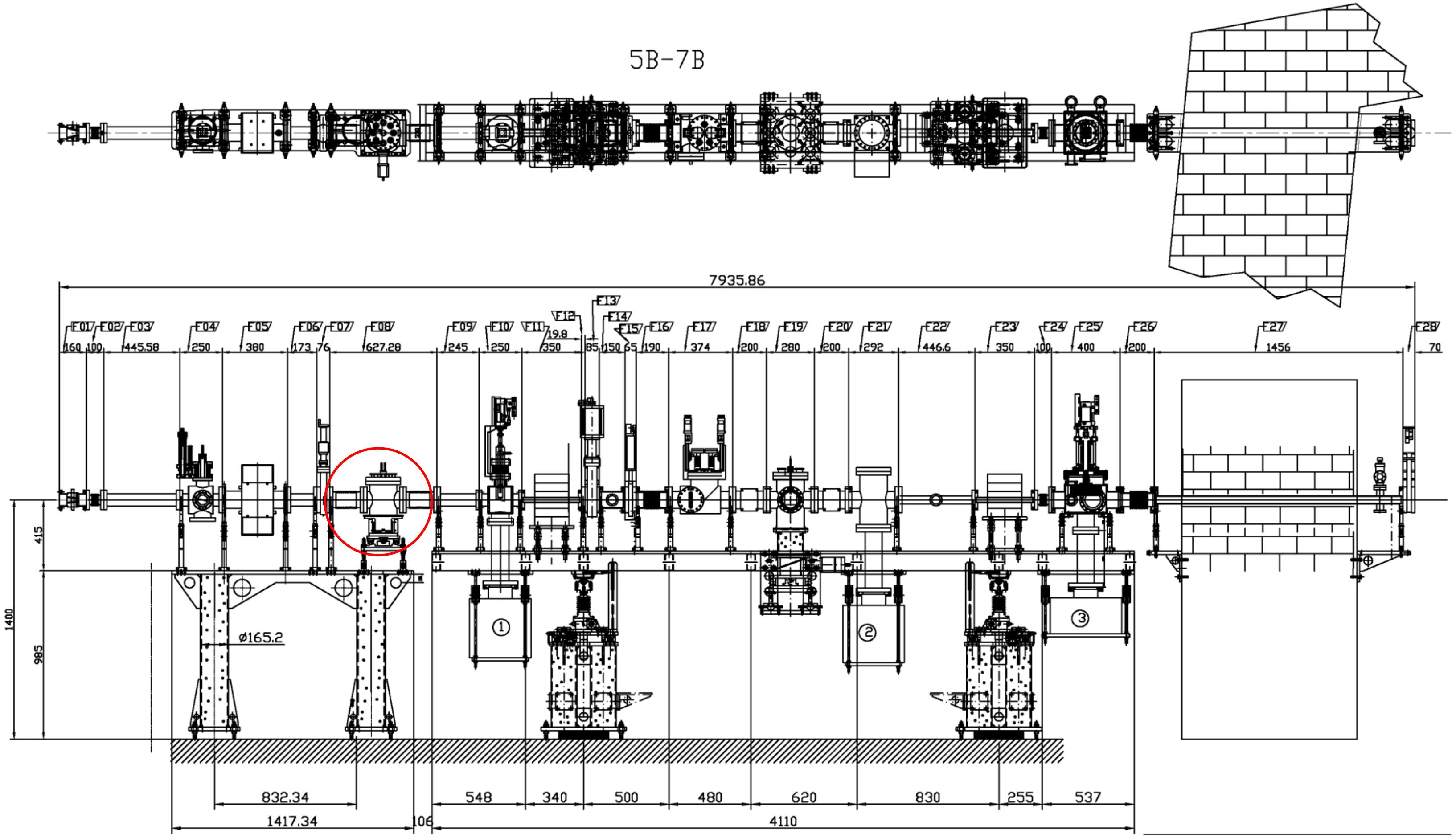
Photon BPM

Photon BPM

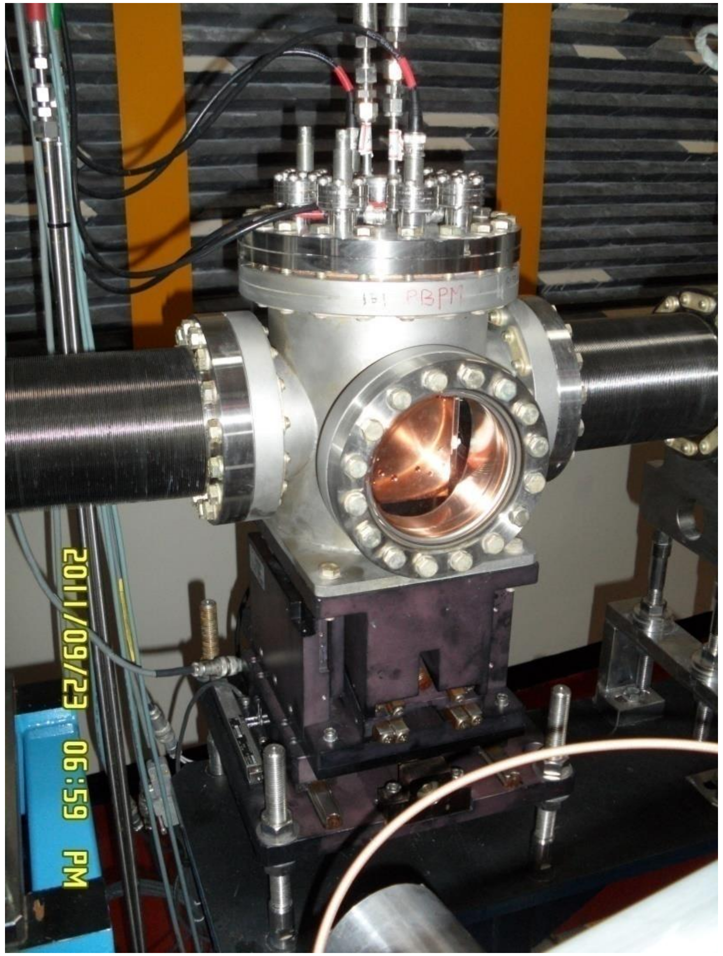


Beam Position $\propto \dfrac{I_{up} - I_{down}}{I_{up} + I_{down}}$

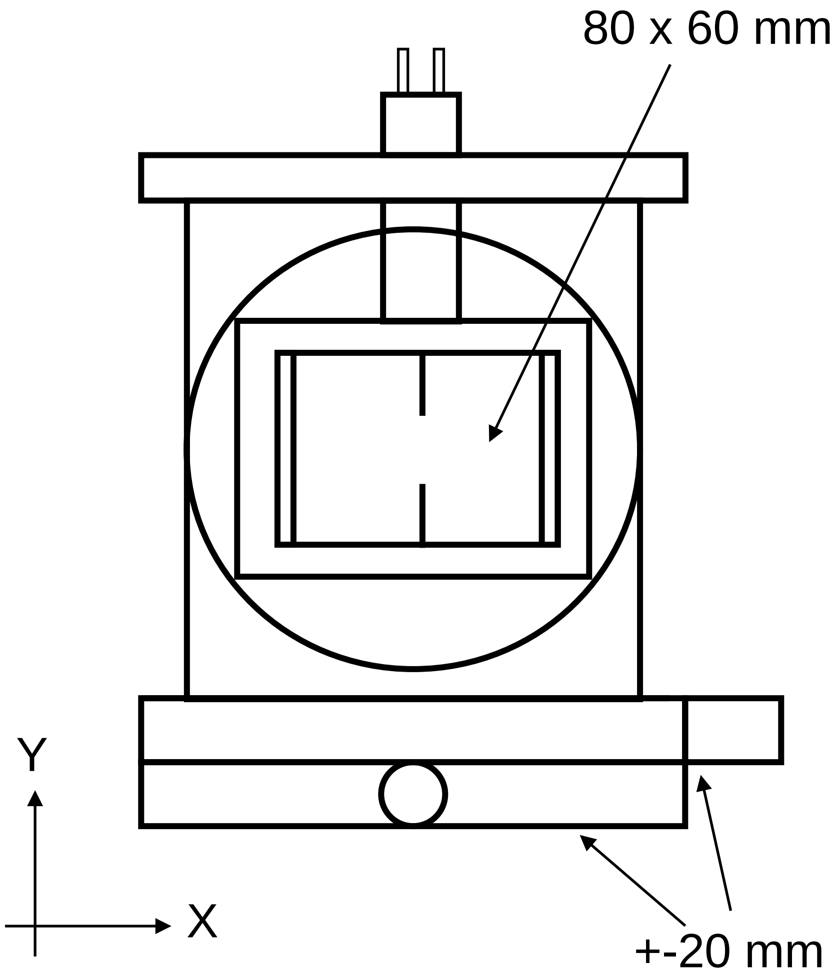
Beam Line Layout (7B Front-end)



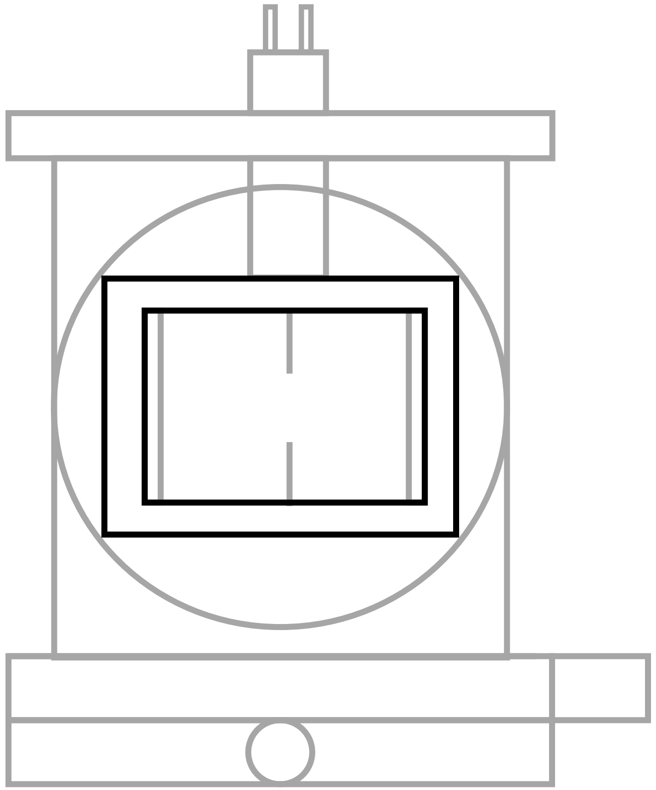
PLS-II Photon BPM



PLS-II PBPM

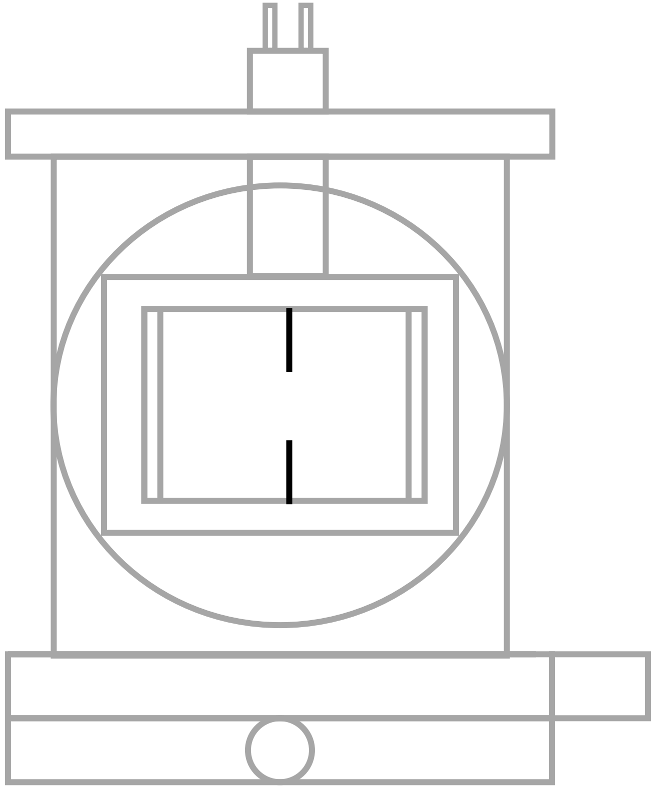


Photon BPM Design



- Copper body
  - 80 x 60 mm^2
- Tungsten blades
  - 0.5 mm thickness
- High voltage electrode
- Water cooling system
- Translation stage
  - Horizontal, vertical

Photon BPM Design



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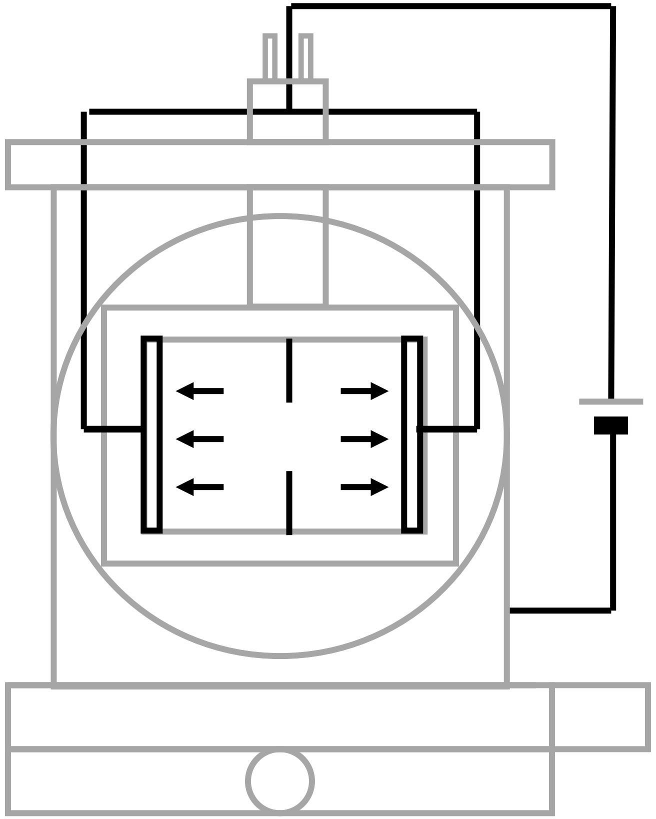
  - 0.5 mm thickness
- High voltage electrode
- Water cooling system
- Translation stage
  - Horizontal, vertical

Photon BPM Design



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- High voltage electrode
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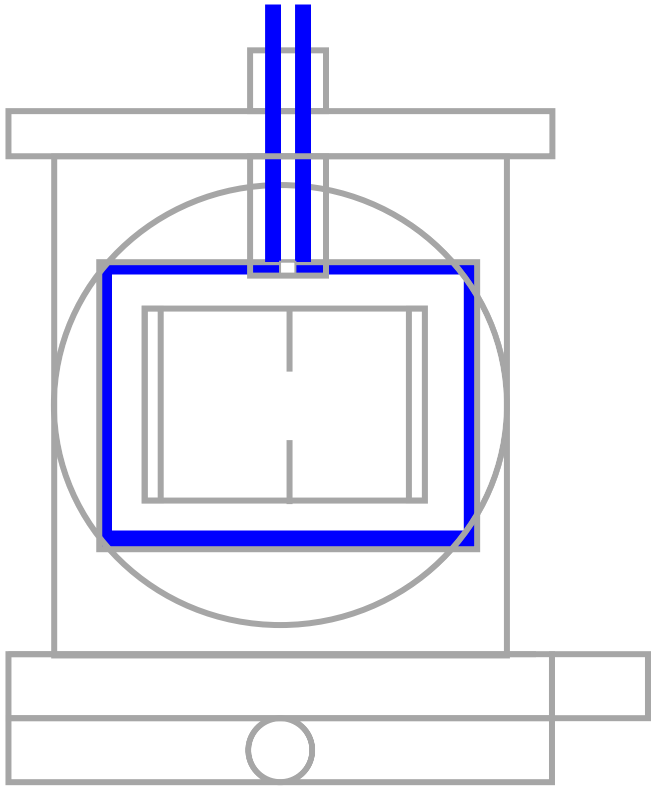
- Translation stage
  - Horizontal, vertical

Photon BPM Design



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- Translation stage
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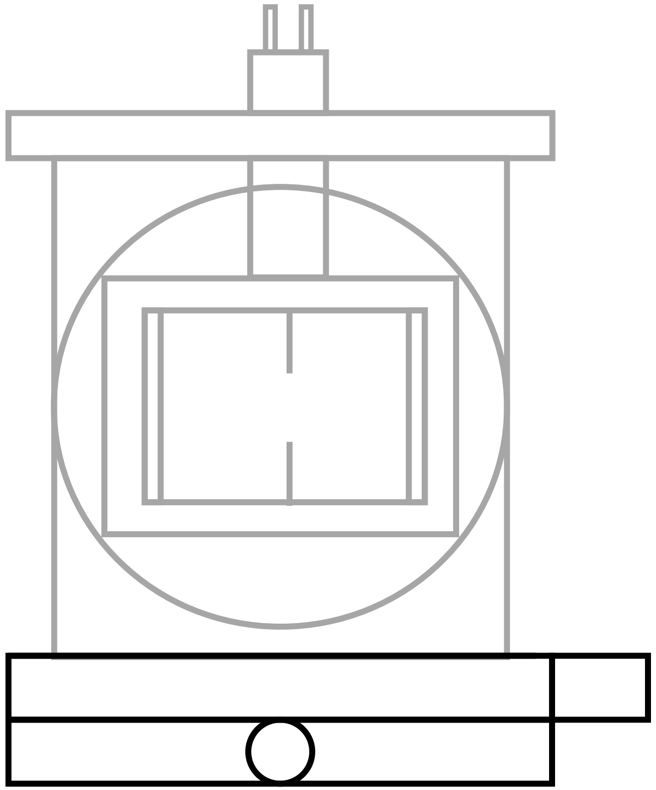
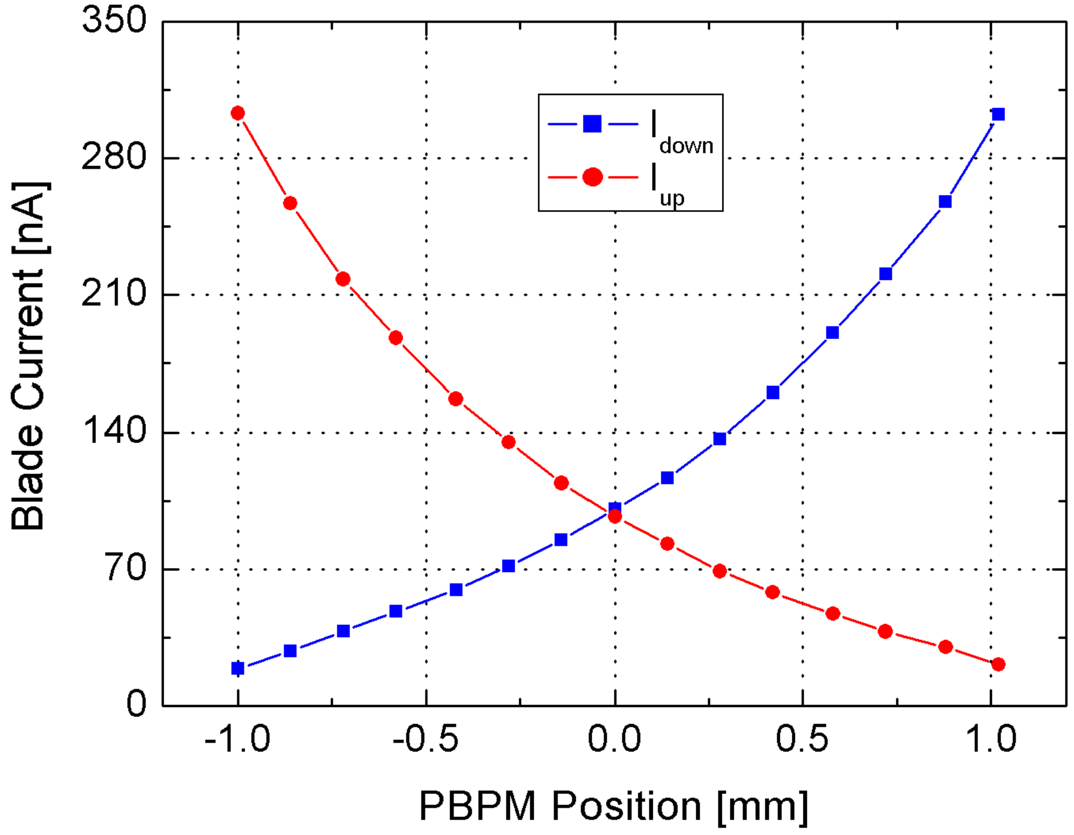
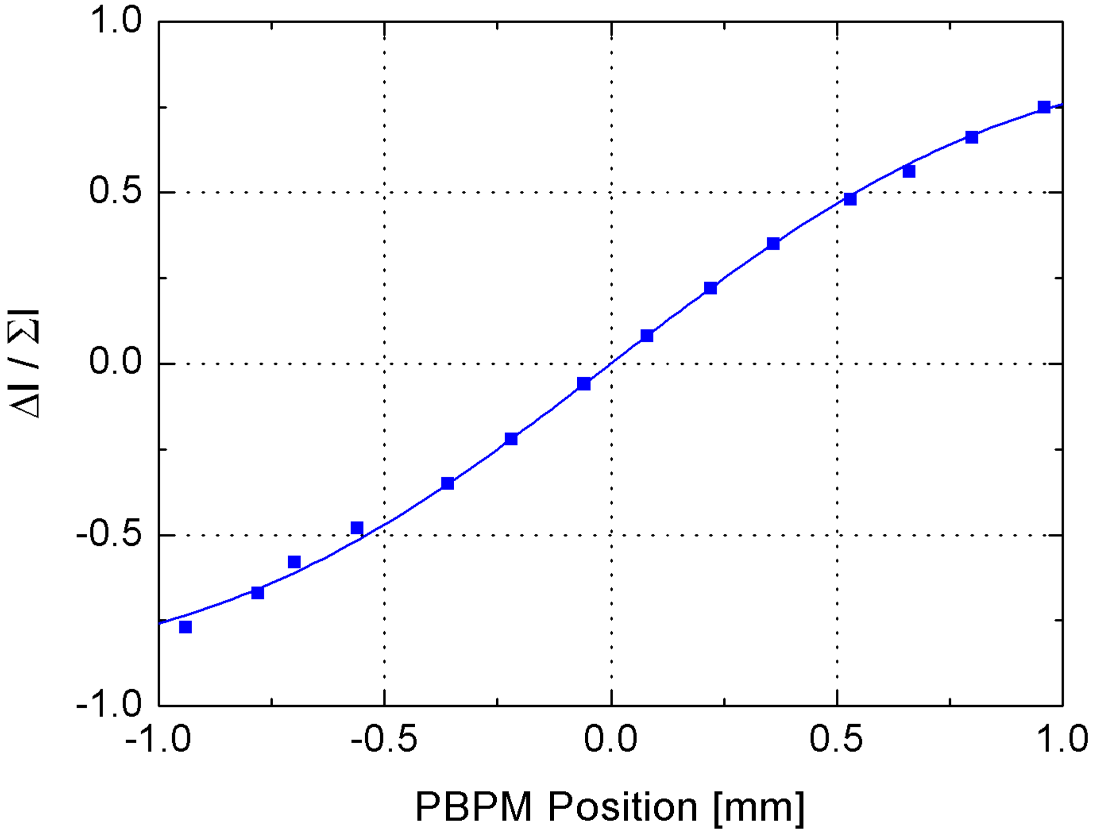
Photon BPM Design



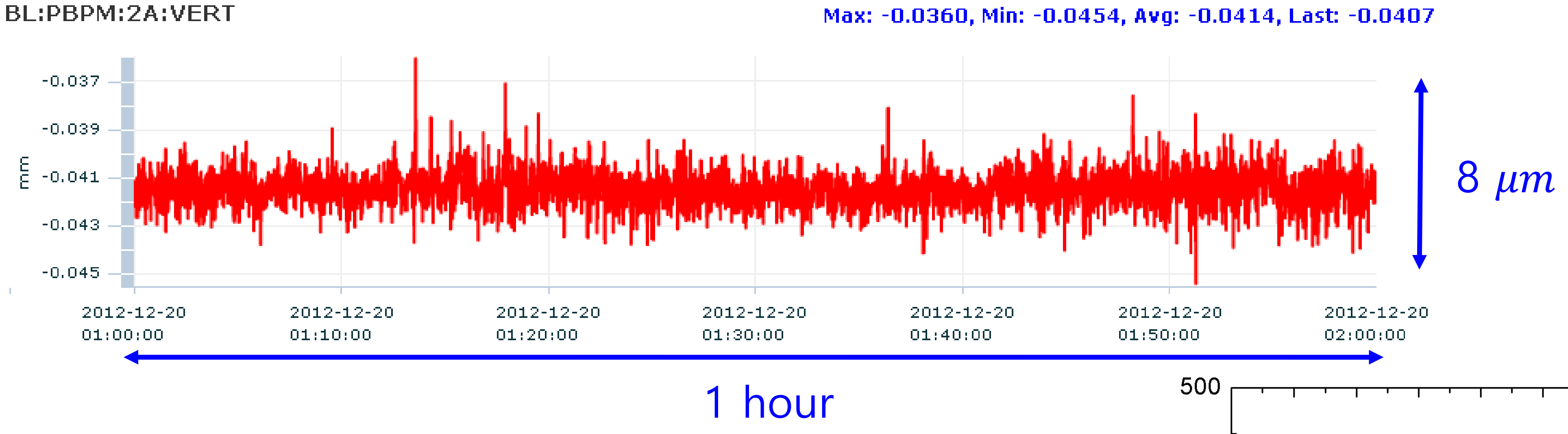
- Copper body
  - 80 x 60 mm^2
- Tungsten blades
  - 0.5 mm thickness
- High voltage electrode
- Water cooling system
- Translation stage
  - Horizontal, vertical

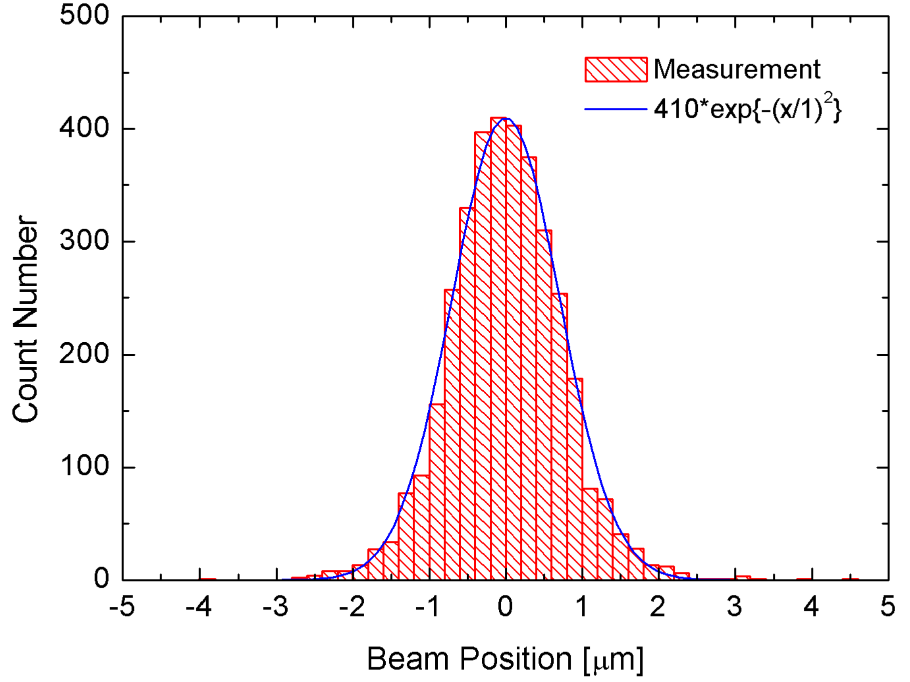
Photon BPM Calibration & Sensitivity





Photon BPM Performance





Beam Position Monitor

- Shoe Box BPM
- Stripline BPM
- Button BPM
- Cavity BPM
- Photon BPM

Wire Test Stand for BPM

실습 과제

- Wire Test Stand 각 장치의 기능을 숙지한다.
- Wire 위치를 변화시키면서 각 Stripline에 걸리는 전압을 관찰한다.
- Wire 위치를 변화시키면서 BPM Reading의 변화를 관찰한다.
- 원점 근처에서 Wire 위치에 따른 BPM Reading은 어떻게 되는가?
- 원점에서 떨어진 곳에서 Wire 위치에 따른 BPM Reading은 어떻게 되는가?
- BPM Reading이 선형적이지 않은 이유를 생각해보자.