# Low-Q IP-BPM

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# INTRODUCTION

## Contents

-The requirement for high resolution BPM

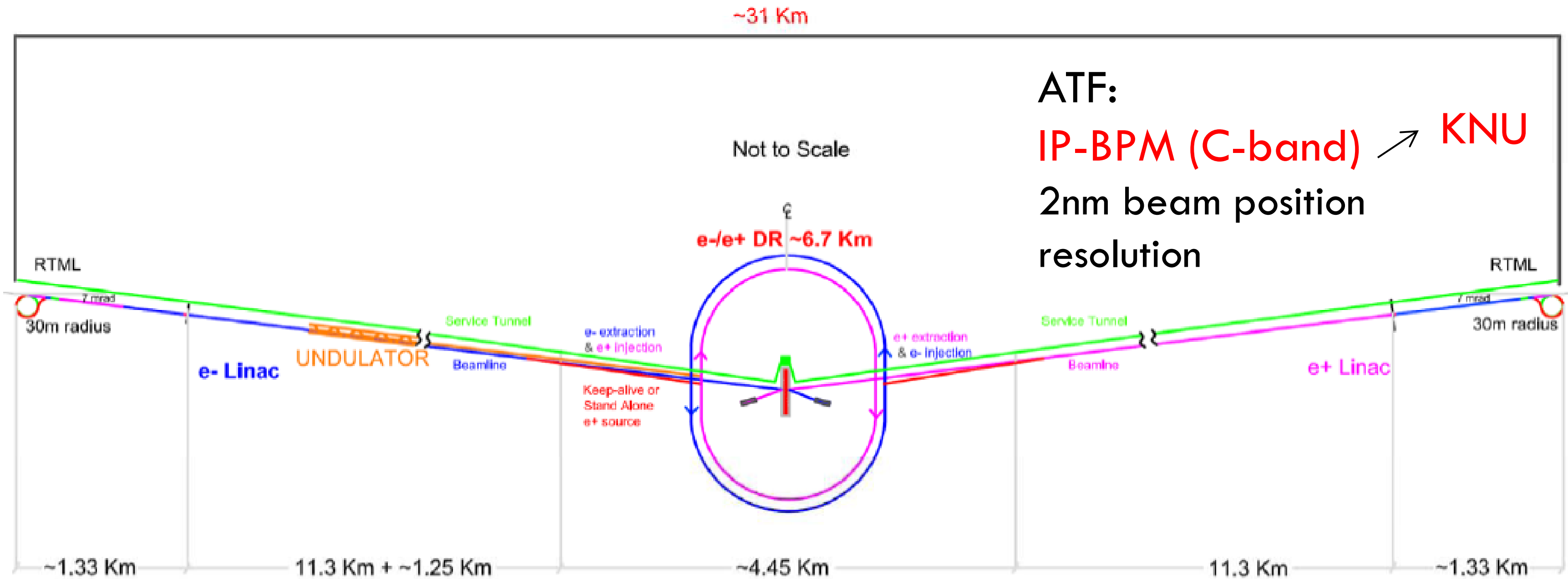
-Principle of cavity BPM

-Parameters for cavity BPM

# Introduction
## - The requirement for high resolution BPM

- Realization of a precise beam handling is strongly required in future accelerators such as linear colliders (LC) and X-ray free electron lasers (XFEL). It goes without saying that a high resolution beam position measurement is the key.

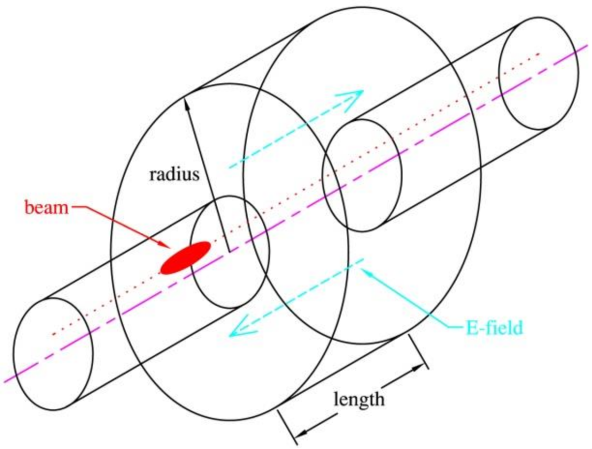
High luminosity ⇨ Small beam size (~ nm level) ⇨ Precise orbit control ( ~nm resolution)

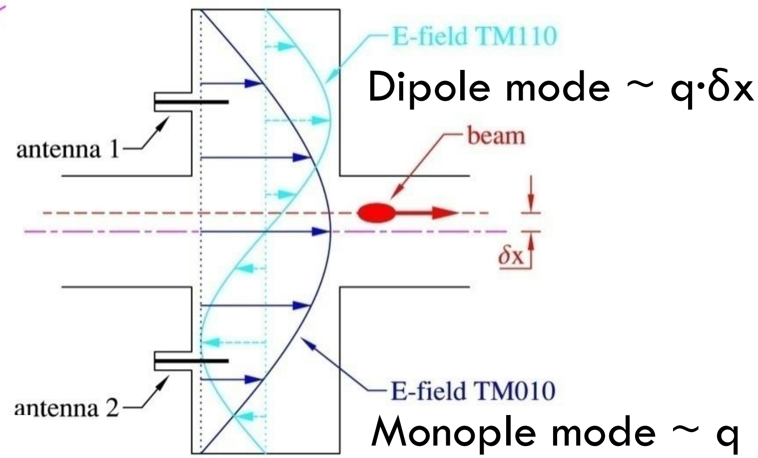


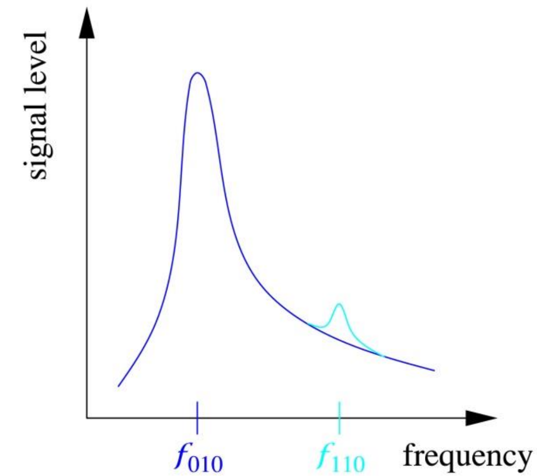

Schematic layout of the ILC complex

# Introduction / Cavity BPM

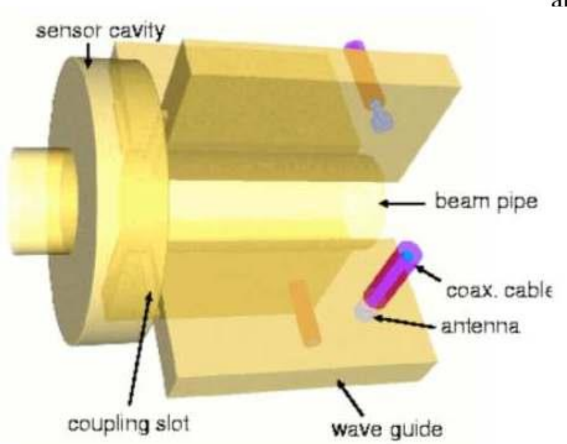
- **Principle** **Generates dipole (TM110) and monopole (TM010) modes**




Needs monopole mode(TM110) suppression!

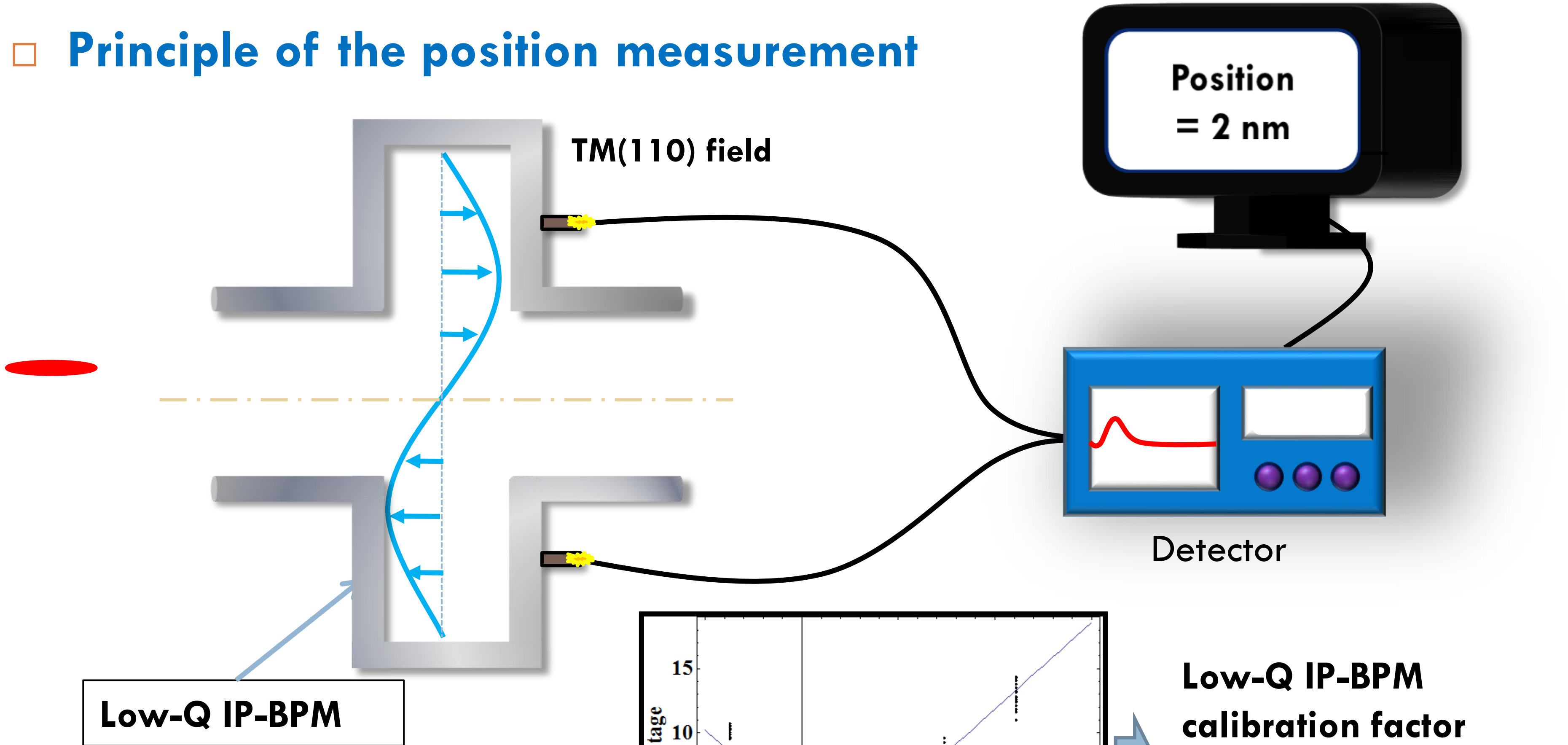


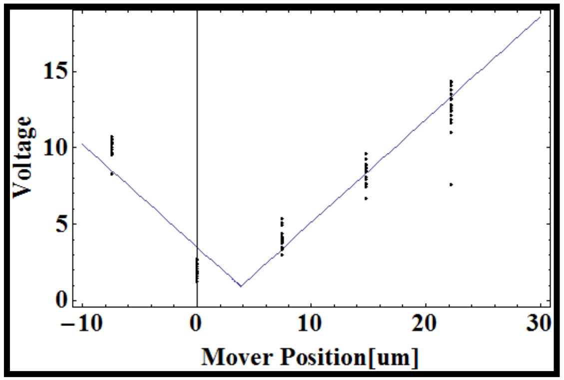

Dipole mode selectable coupler

1. **Small thermal noise due to narrow band width (~ MHz).**
2. **No signal at zero position.**
3. **Position is calculated with the dipole mode of cavity pickup**
4. **Normalization from different signal (monopole mode).**

# Introduction / Cavity BPM

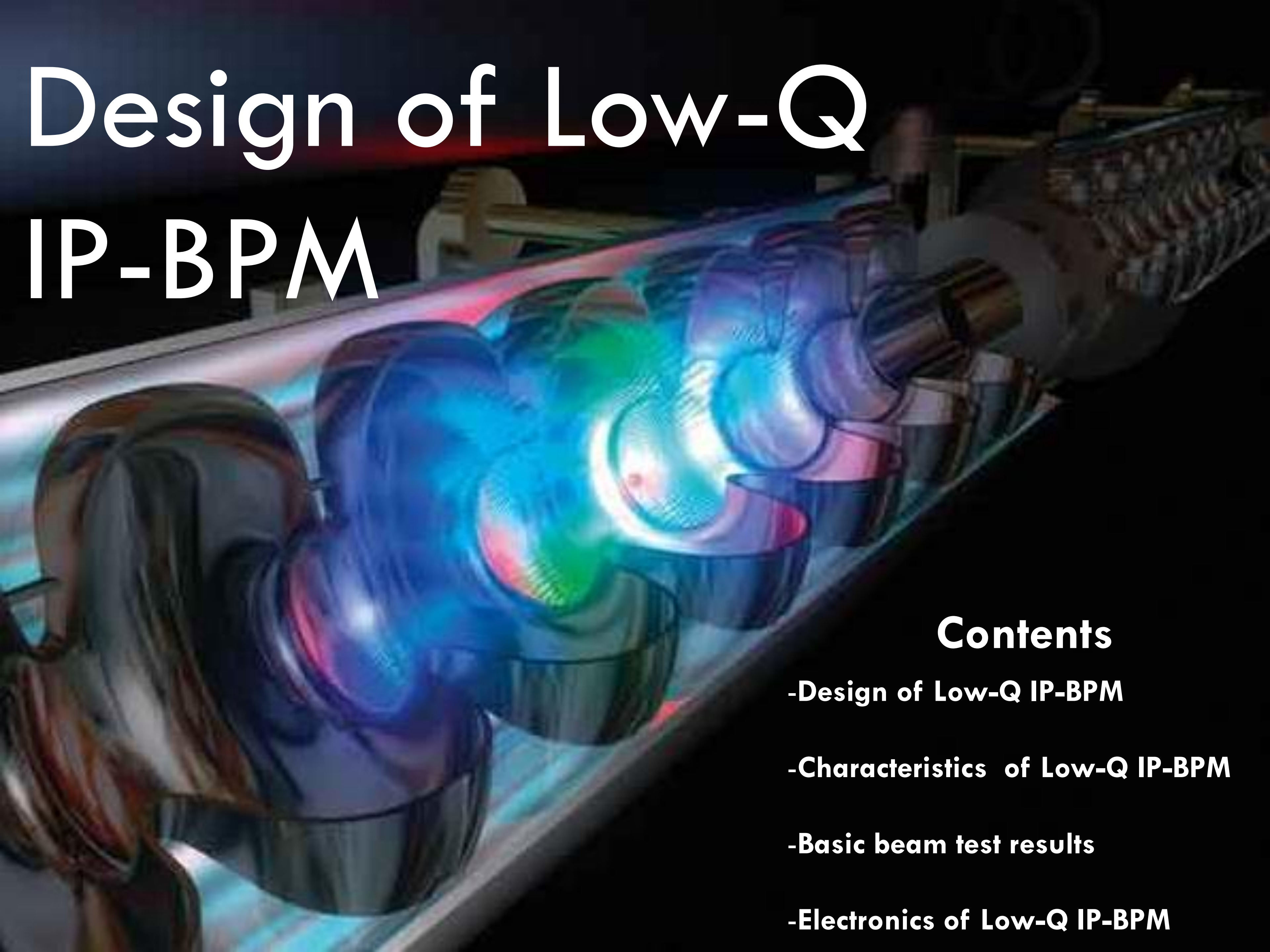
- Principle of the position measurement




Low-Q IP-BPM calibration factor = 0.674mV/nm

# Design of Low-Q IP-BPM



## Contents

-Design of Low-Q IP-BPM

-Characteristics of Low-Q IP-BPM

-Basic beam test results

-Electronics of Low-Q IP-BPM

# Design of Low-Q IP-BPM

- **The rectangular design is determined since f0 for TM210 or TM120 is mainly determined by cavity size in X and Y direction, a and b. From simulation and measurements of test cavities, a = 60.99 mm and b = 48.59 mm were determined.**

| Parameters | Length[mm] |
|---|---|
| X direction (= a) | 60.99 |
| Y direction (= b) | 48.59 |
| Z direction (= L) | 5.8 |
| X-beam pipe | 12 |
| Y-beam pipe | 6 |

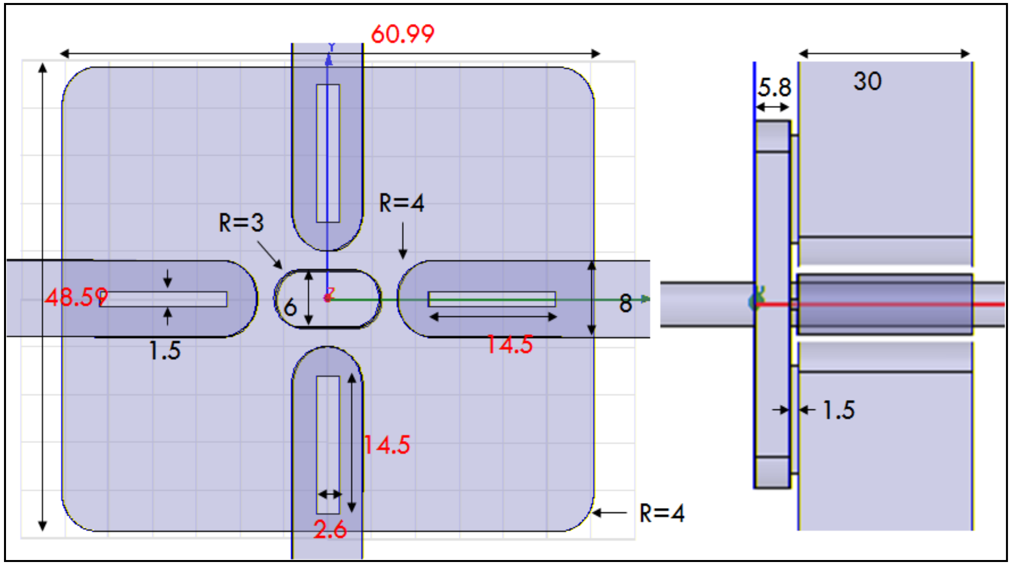


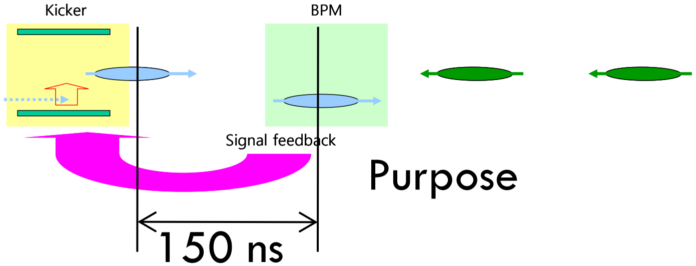

Figure 1: Dimension of cavity

The cavity length *L has to be shortened in order to reduce angle* sensitivity. However, shorter *L decreases R/Q, which reduces position* sensitivity also. To recover position sensitivity, *Rp is required to be small, in order to prevent* leakage of the field from the cavity.

# Design of Low-Q IP-BPM

## Characteristics

1. Same basic idea with KEK IP-BPM.
2. Short decay time 20 ns for x and y signals.
3. Short decay time 30 ns for reference signal.
4. Single stage homodyne down convertor.
5. L.O. signal from reference cavity.




Purpose

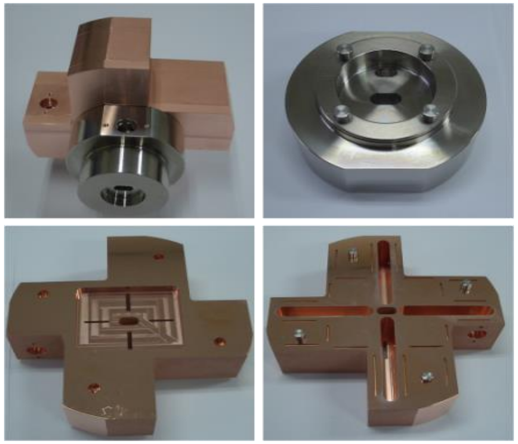
Design parameter

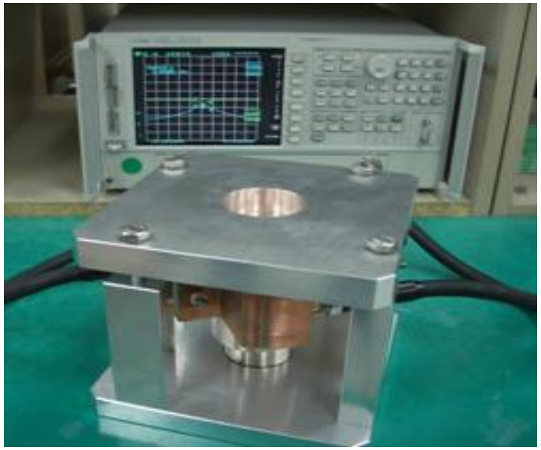
| Port | f (GHz) | b | $Q_0$ | $Q_{ext}$ |
|---|---|---|---|---|
| X | 5.712 | 8 | 5900 | 730 |
| Y | 6.426 | 9 | 6020 | 670 |
| Reference | 6.426 | 0.0117 | 1170 | 100250 |

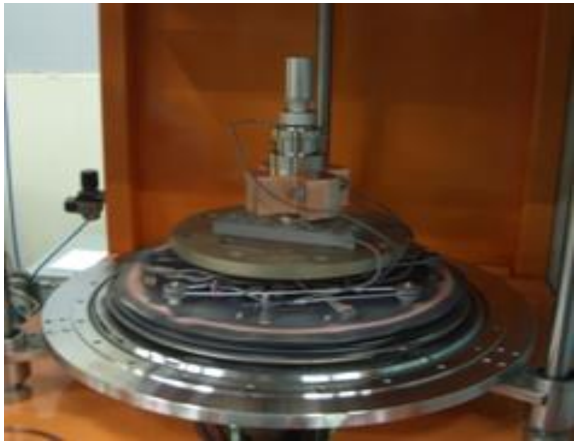
$$\frac{1}{Q_L}\left(=\frac{1}{\omega\tau}\right)=\frac{1}{Q_0}+\frac{1}{Q_{ext}}$$

Multi bunch measurement due to Short decay time(~low Q value)

## Development

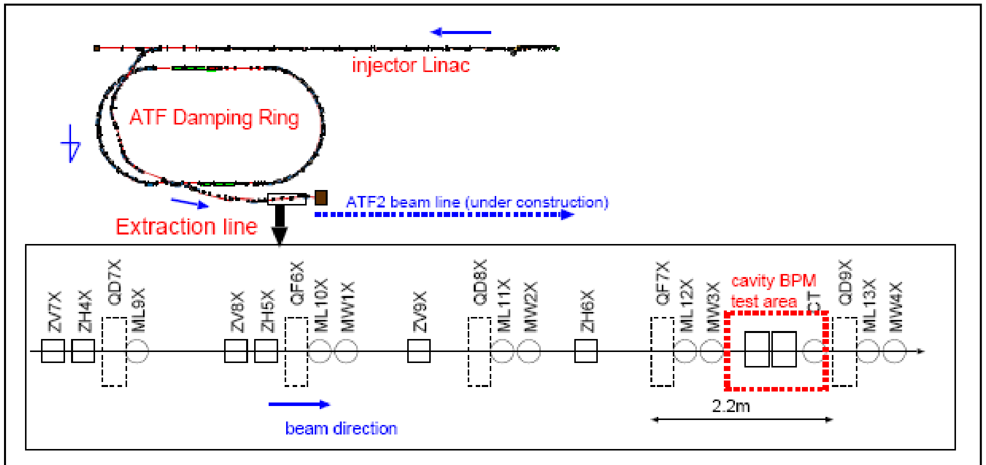


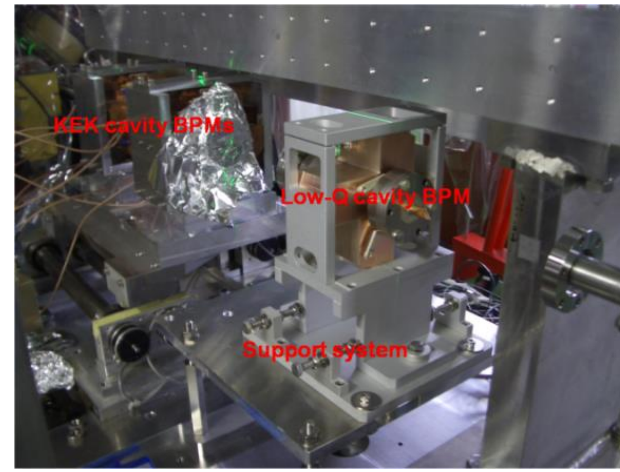


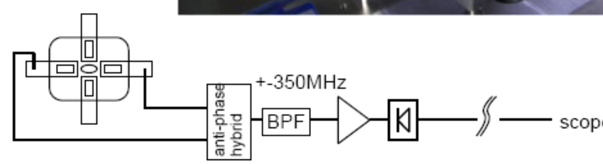


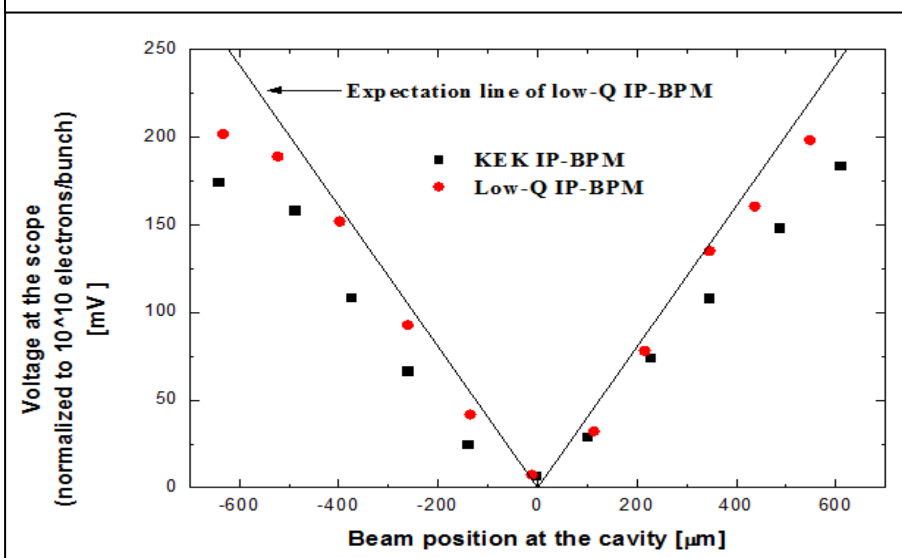
# Basic beam test of low-Q IP-BPM

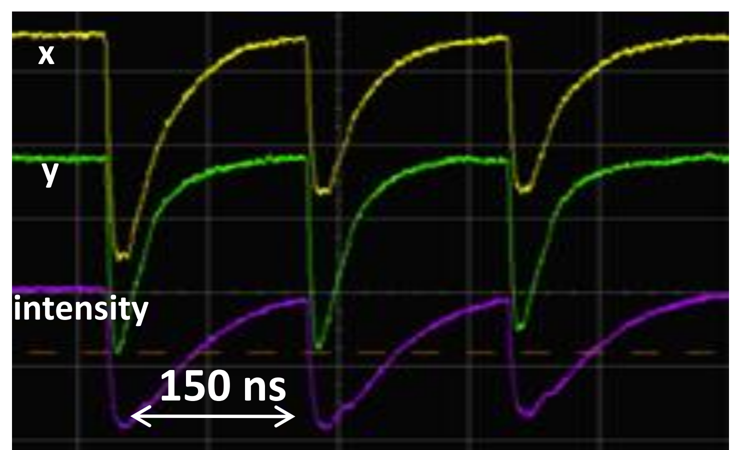
## BPM sensitivity measurement



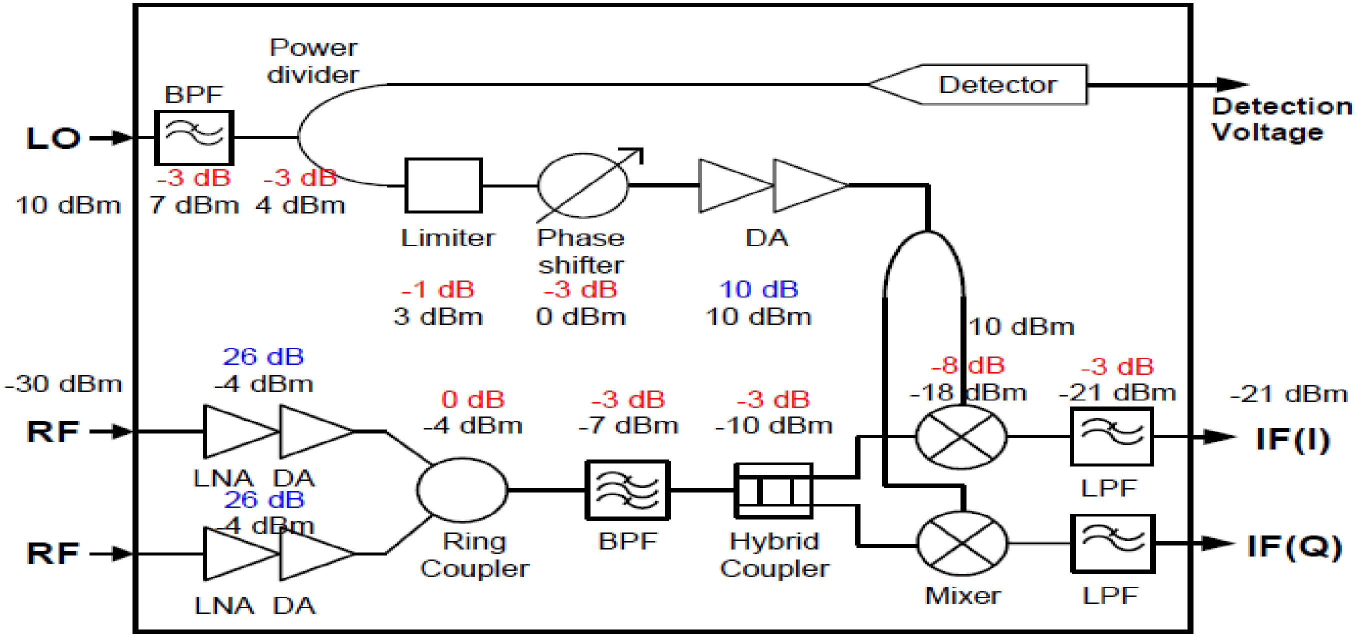



# Electronics for Y-ports

## Scheme of electronics of IP-BPM




- Conversion Gain : 10 dB
- Measured N.F

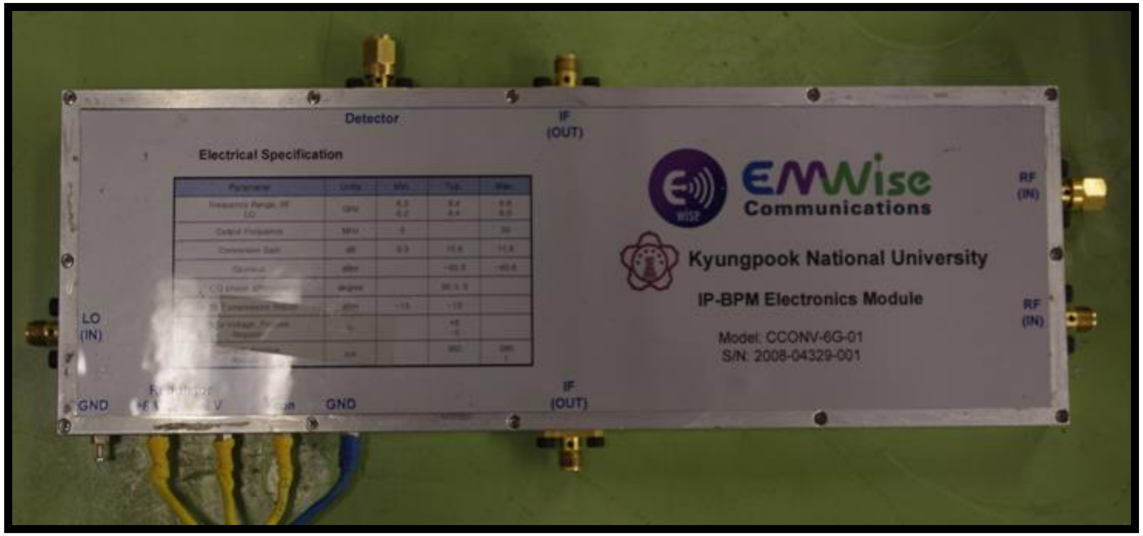
| Used devices | Measured N.F. |
|---|---|
| N.F. analyzer | 5 dB |
| S/G & S/A | 19 dB |

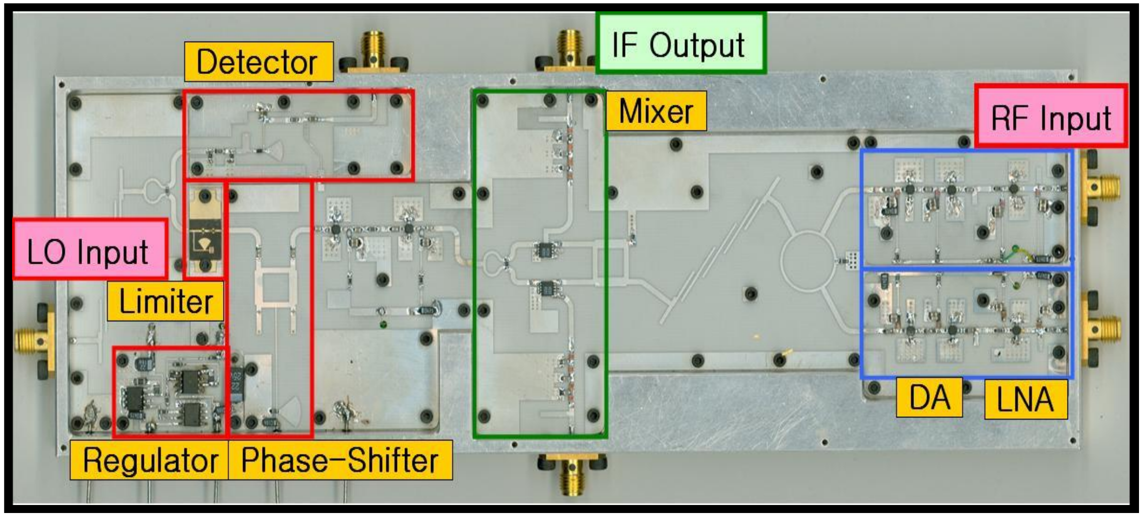
- BW of LPF : 50MHz
- Estimated position resolution

| N.F | Estimated Resolution |
|---|---|
| 0 dB | 3 nm |
| 5 dB | 4 nm |
| 19 dB | 20 nm |

- Measured Latency : 17ns

# Electronics for Y-ports




## Y-port Electronics

**I-Q signal with 90° deference**

**I-Q tuning by phase shifter**

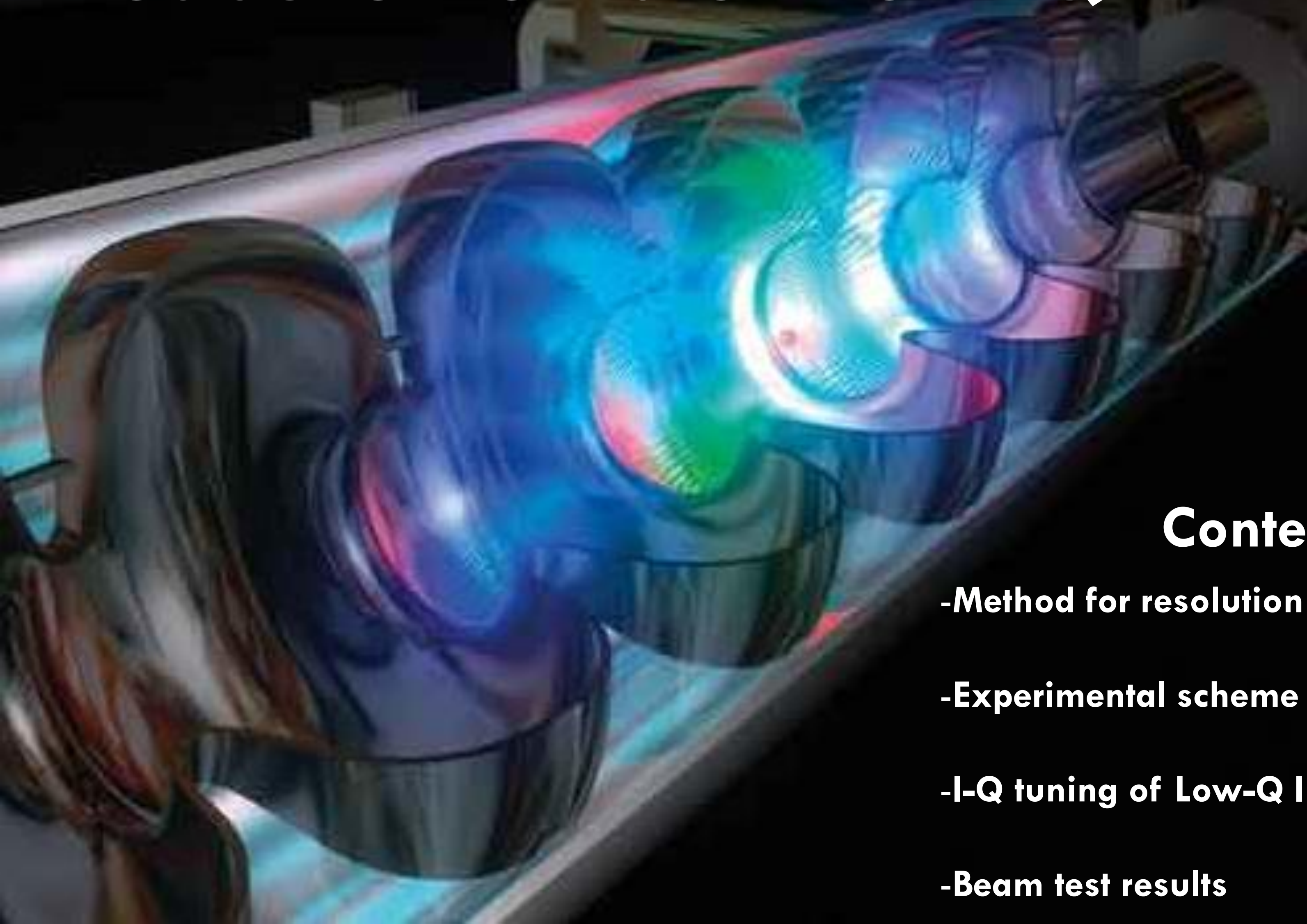
**- 20ns decay time for feedback System.**

**Design Frequency**

**LO: 6426 MHz**

**RF: 6426 MHz**

# Beam position resolution measurements of Low-Q IP-BPM



## Contents

-Method for resolution study

-Experimental scheme for beam test

-I-Q tuning of Low-Q IP-BPM

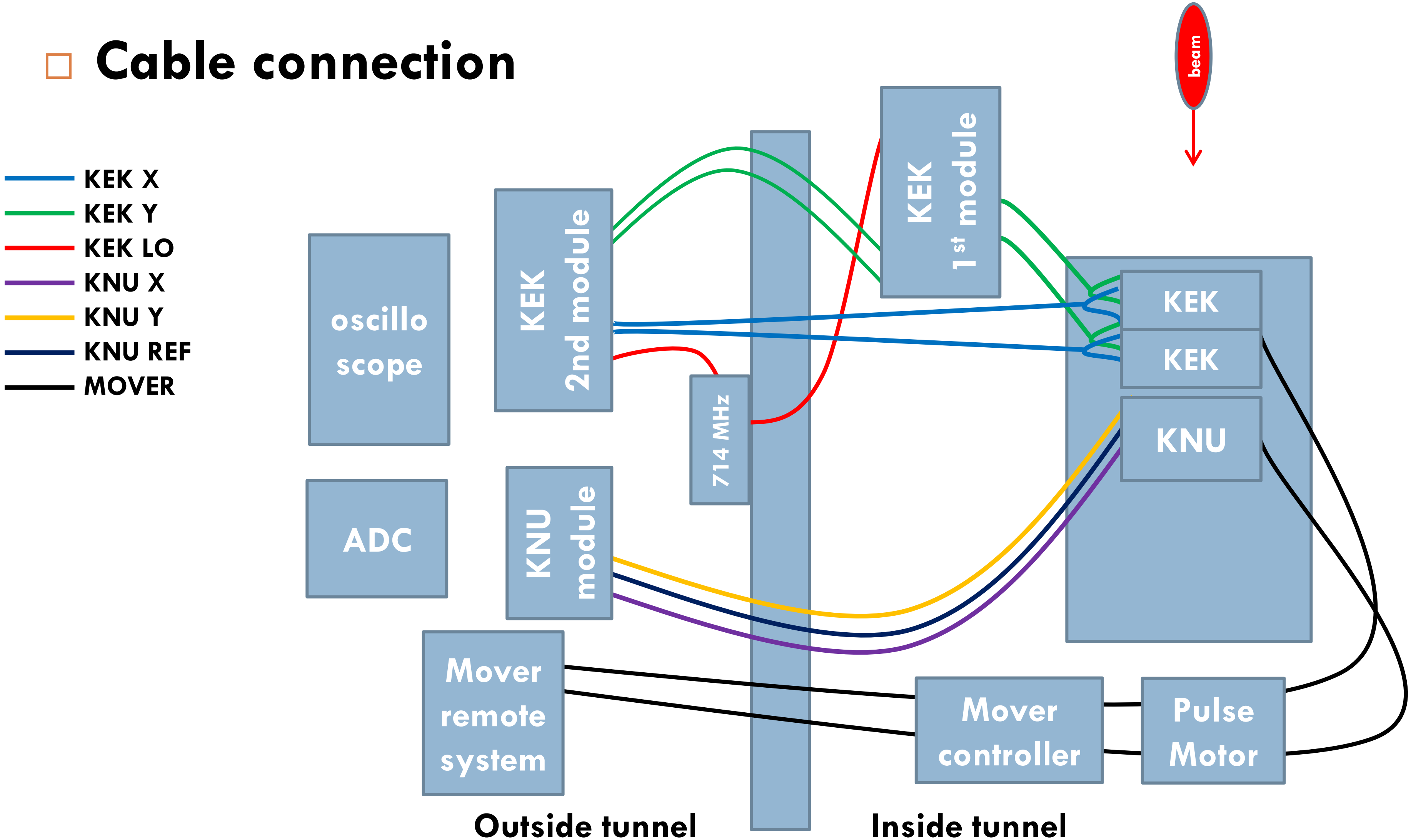
-Beam test results

# Beam position resolution measurements of Low-Q IP-BPM

- **Oscilloscope method for resolution study**
  - Calibration run
    - KNU electronics set-up: 40dB_Amp
    - KEK electronics set-up: with out Att
    - I-Q tuning for KEK BPM1,2 & KNU BPM
    - Search for each BPMs center (BPM1->BPM2->KNU)
    - Calibration run for each BPMs
  - Resolution run
    - All the BPMs are set to have an offset.

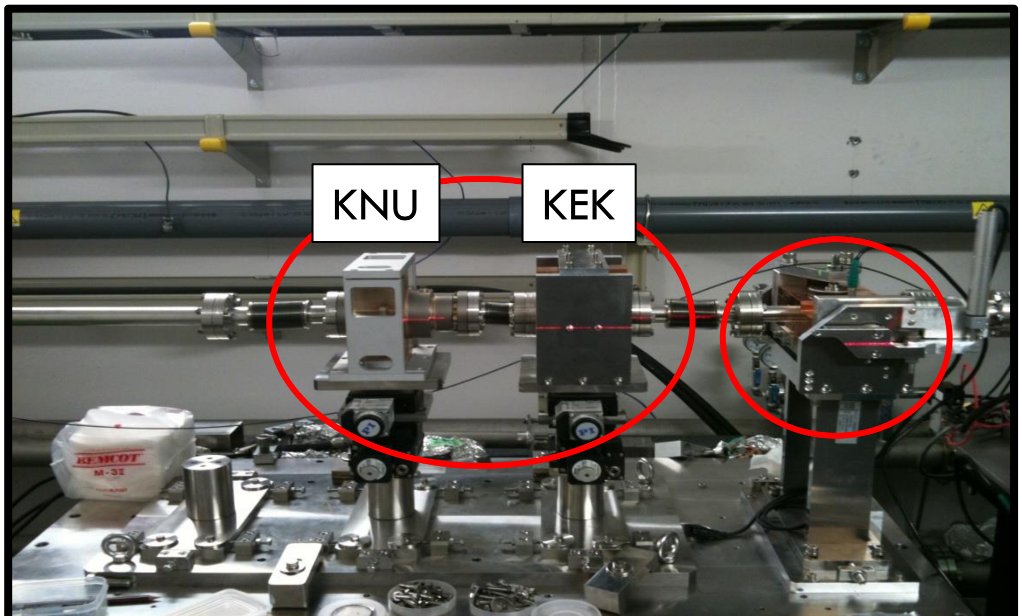
# Experimental scheme for beam test

- Cable connection

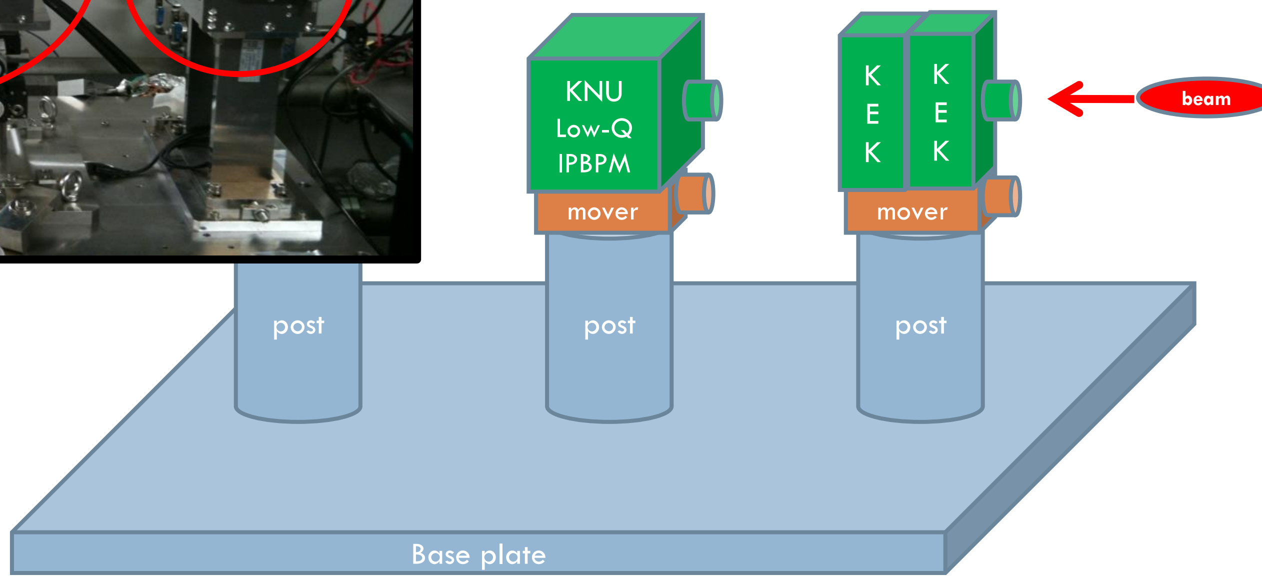


# Bema position resolution measurements of Low-Q IP-BPM

- **Low-Q IP-BPM Layout** (1 KNU IP-BPM + 2 KEK IP-BPM )




**KNU Low-Q IP-BPM**
**KEK BPMs x2**
**Reference BPM**
**Horizontal mover x2**
**Vertical mover x2**

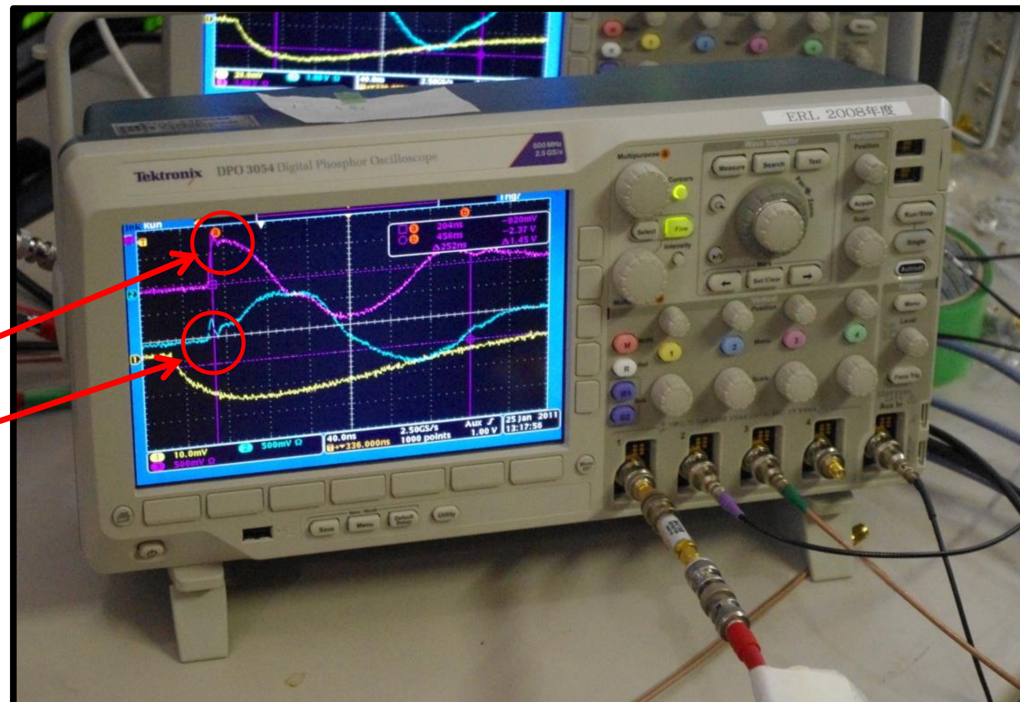


# Bema position resolution measurements of Low-Q IP-BPM

## I-Q tuning of KEK BPM1,2 & KNU BPM

- **I-Q tuning was performed by using oscilloscope.**

**When I signal shows the maximum position, Q signal was set to minimum position by using phase shifter.**

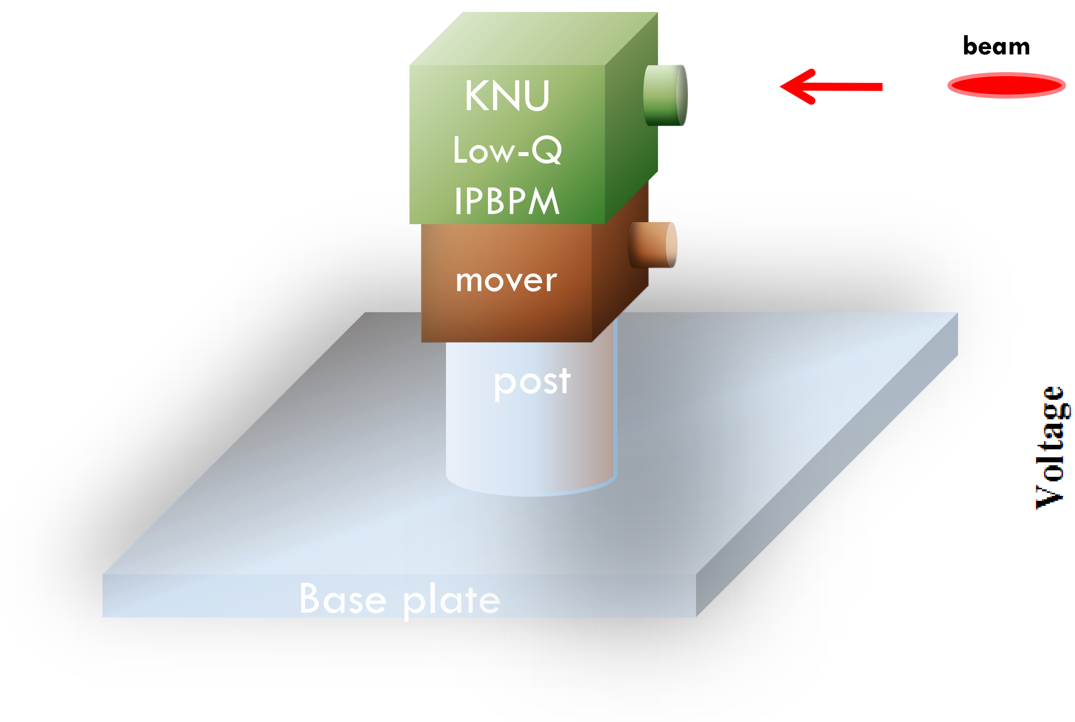



**I-signal**

**Q-signal**

# Bema position resolution measurements of Low-Q IP-BPM

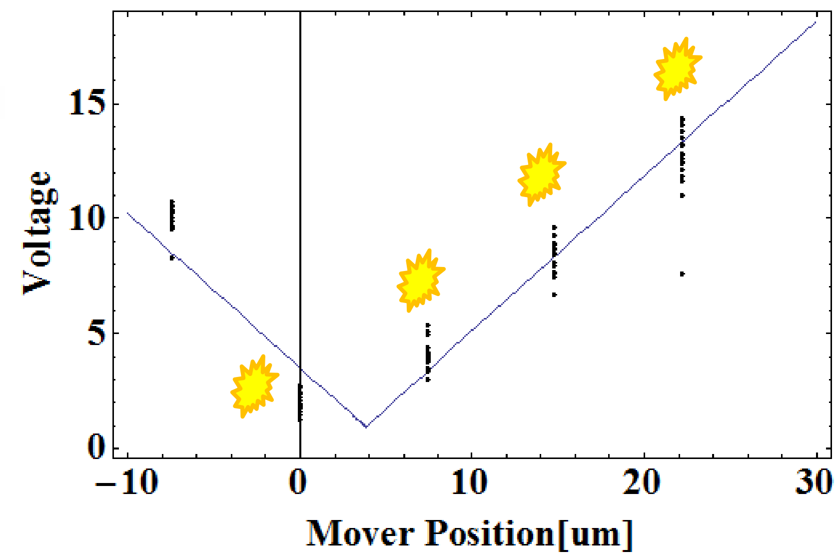
## IP-BPM calibration beam test




**KNU IP-BPM**

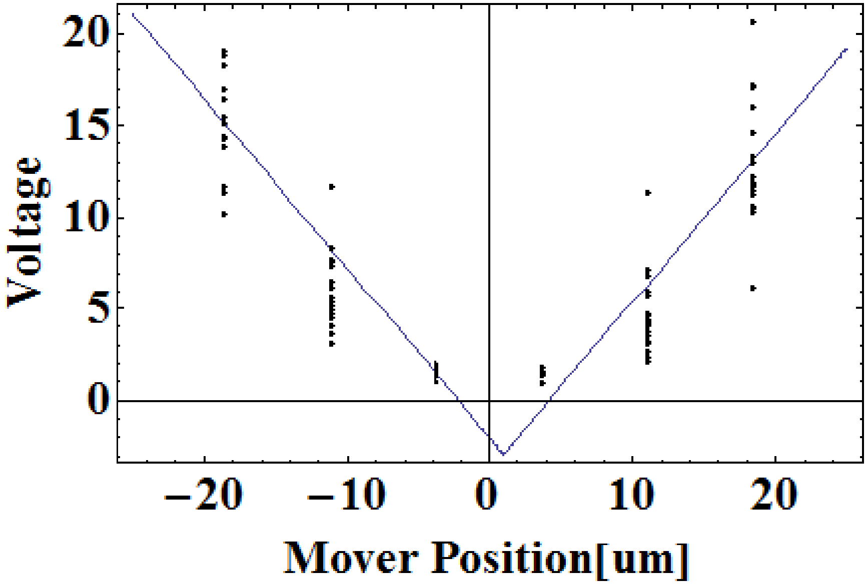
**0.674 V/um**

| | Estimate | Standard Error | t Statistic | P-Value |
|---|---|---|---|---|
| a53 | 0.673998 | 0.0264348 | 25.4966 | $8.65262 \times 10^{-45}$ |
| b53 | −3.79521 | 0.220476 | −17.2137 | $3.0282 \times 10^{-31}$ |
| c53 | 0.931853 | 0.282349 | 3.30036 | 0.0013518 |



# BPM calibration by using mover

| | Estimate | Standard Error | t Statistic | P-Value |
|---|---|---|---|---|
| a53 | 0.922552 | 0.0450848 | 20.4626 | $1.84298 \times 10^{-40}$ |
| b53 | −1.00327 | 0.299317 | −3.35187 | 0.00108159 |
| c53 | −2.92423 | 0.569777 | −5.13223 | $1.15154 \times 10^{-6}$ |



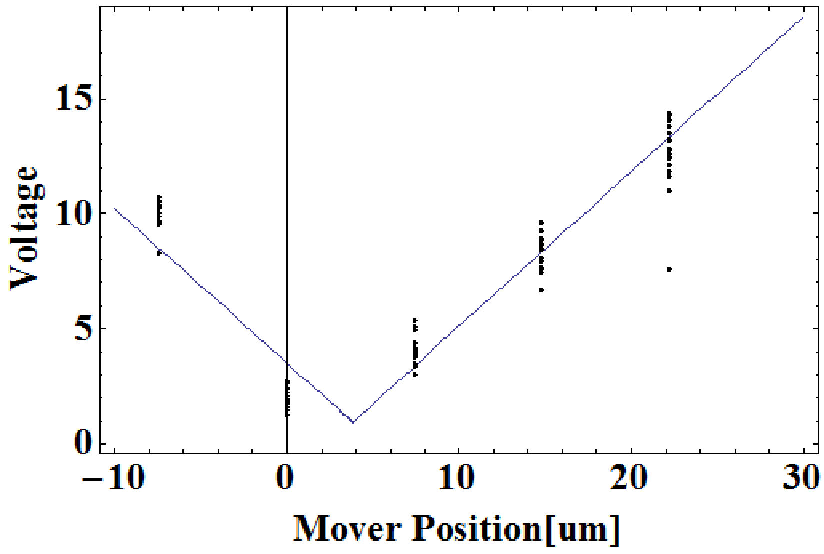

**KEK IP-BPM**

**0.922 V/um**

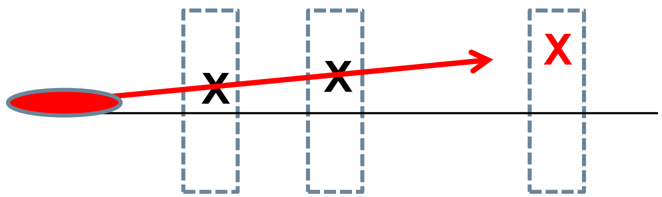
**KNU IP-BPM**

**0.674 V/um**

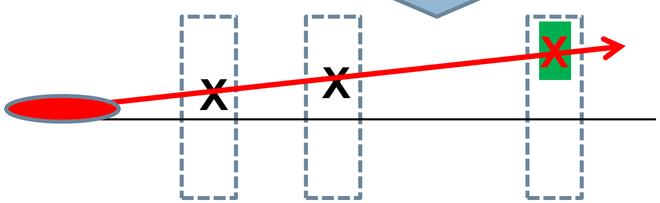
| | Estimate | Standard Error | t Statistic | P-Value |
|---|---|---|---|---|
| a53 | 0.673998 | 0.0264348 | 25.4966 | $8.65262 \times 10^{-45}$ |
| b53 | −3.79521 | 0.220476 | −17.2137 | $3.0282 \times 10^{-31}$ |
| c53 | 0.931853 | 0.282349 | 3.30036 | 0.0013518 |



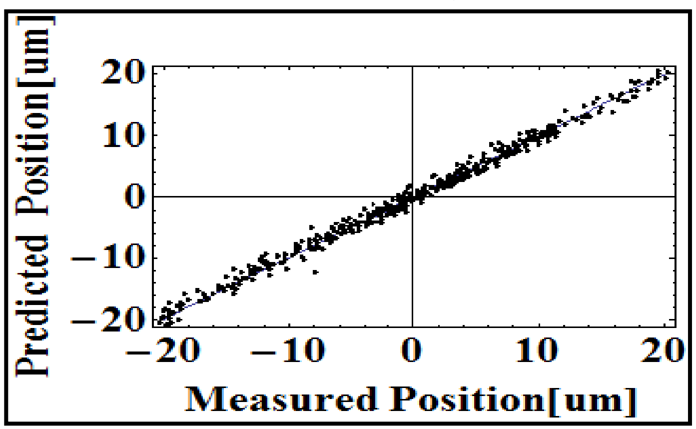
# Results of Jan. beam(2011) resolution test



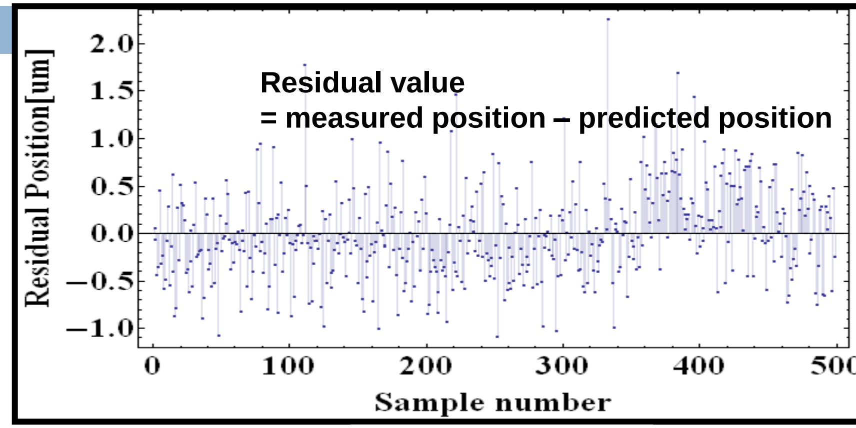

Beam position prediction




Beam position measurement

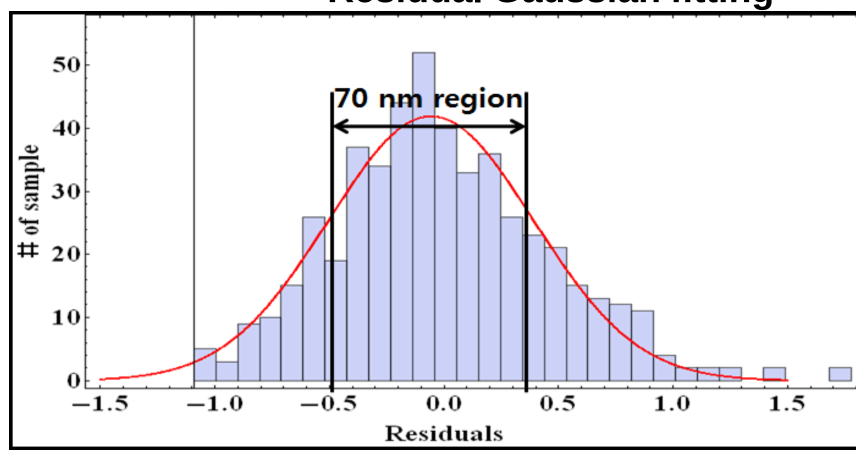



Convert to residual




Sampling number

Residual Gaussian fitting




$$\text{Resolution} = \frac{\text{Residual}}{\text{Calibration factor}} = \boxed{70.44\,\text{nm}}$$

Limitation of Old Low-Q IP-BPM system = ~10nm

# New Low-Q IP-BPM

## Contents

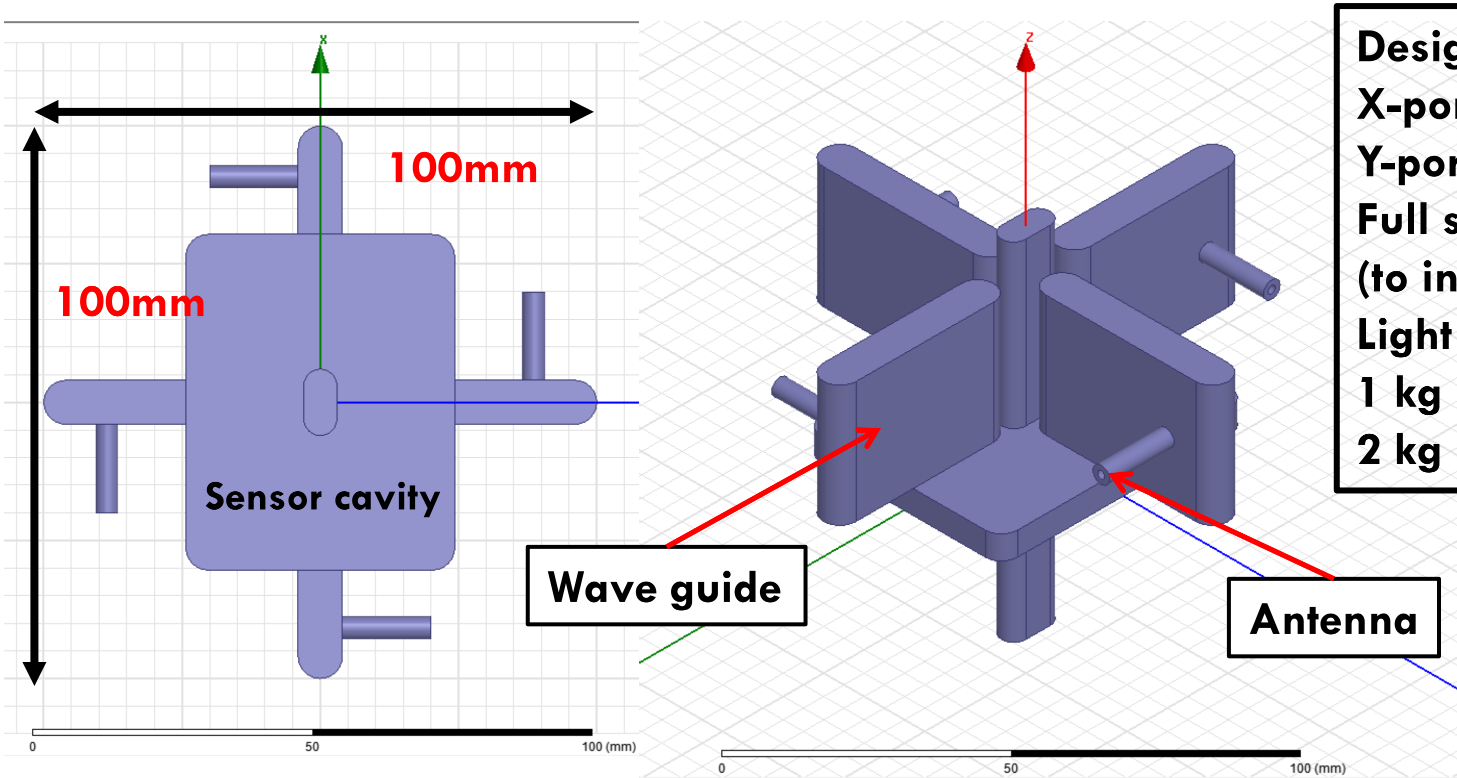
- Design of New Low-Q IP-BPM
- RF test of New Low-Q IP-BPMs
- New electronics of Low-Q IP-BPM
- Basic beam test results

# Motivation of 11cm Low-Q IP-BPM design

- 11cm Low-Q IP-BPM
  - Old Low-Q IP-BPM was fabricated by copper with 14cm x 14cm size. However, this cavity BPM has too heavy weight to install inside IP-chamber. Therefore, we need more small size and light weight cavity BPM to install inside IP-chamber!
  - First, we changed material of IP-BPM from copper to Aluminum to make light weight.
  - After then, the size of cavity BPM was reduced from 14cm x 14cm to 11cm x 11cm with out any performance disadvantage.

# 11cm Low-Q IP-BPM design

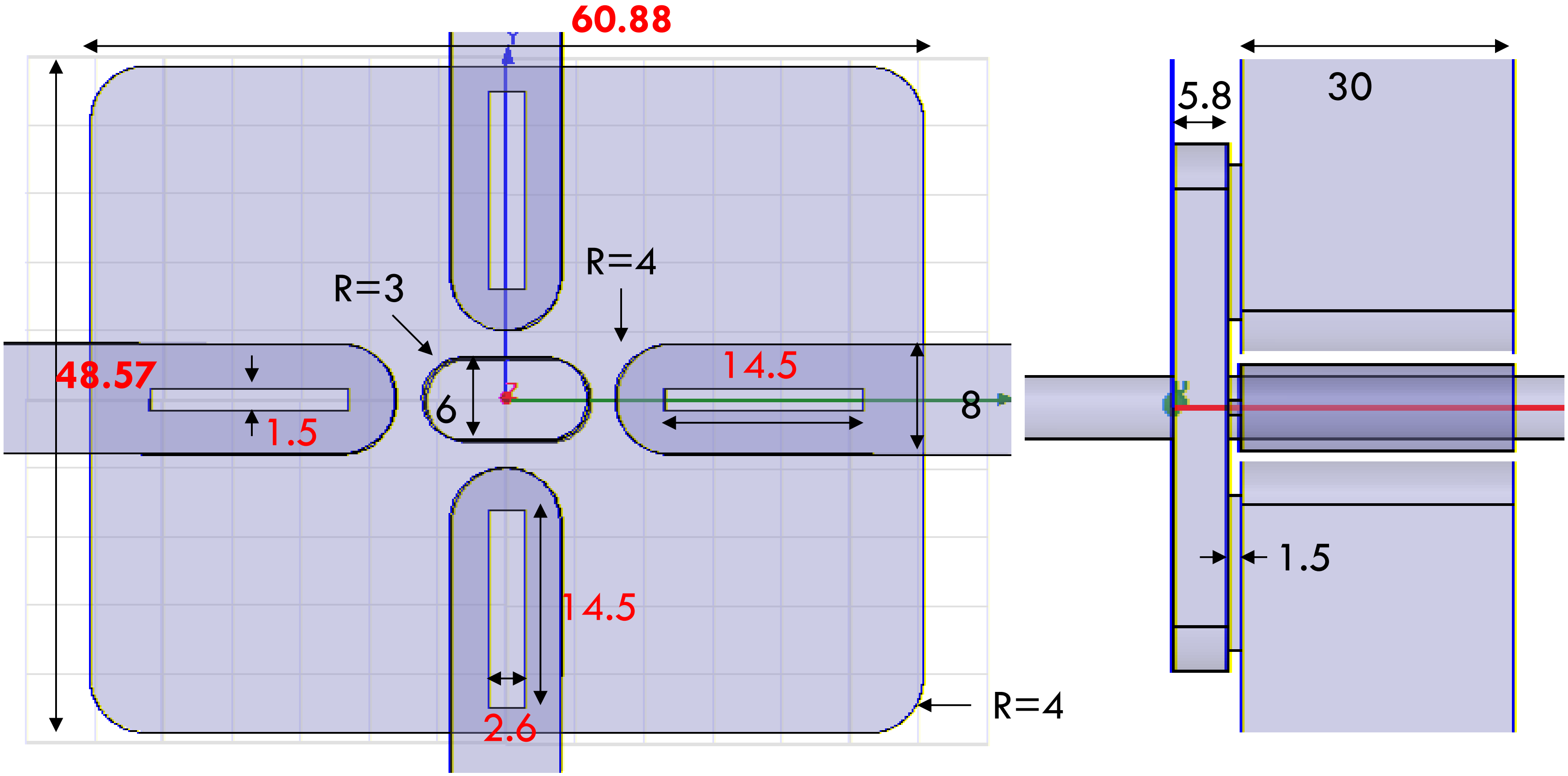
- 11cm Low-Q IP-BPM drawings of HFSS




Designed frequency
X-port: 5.712 GHz
Y-port: 6.426 GHz
Full size : 11cmx11cm
(to install IP-Chamber)
Light weight:
1 kg (Single)
2 kg (Double)

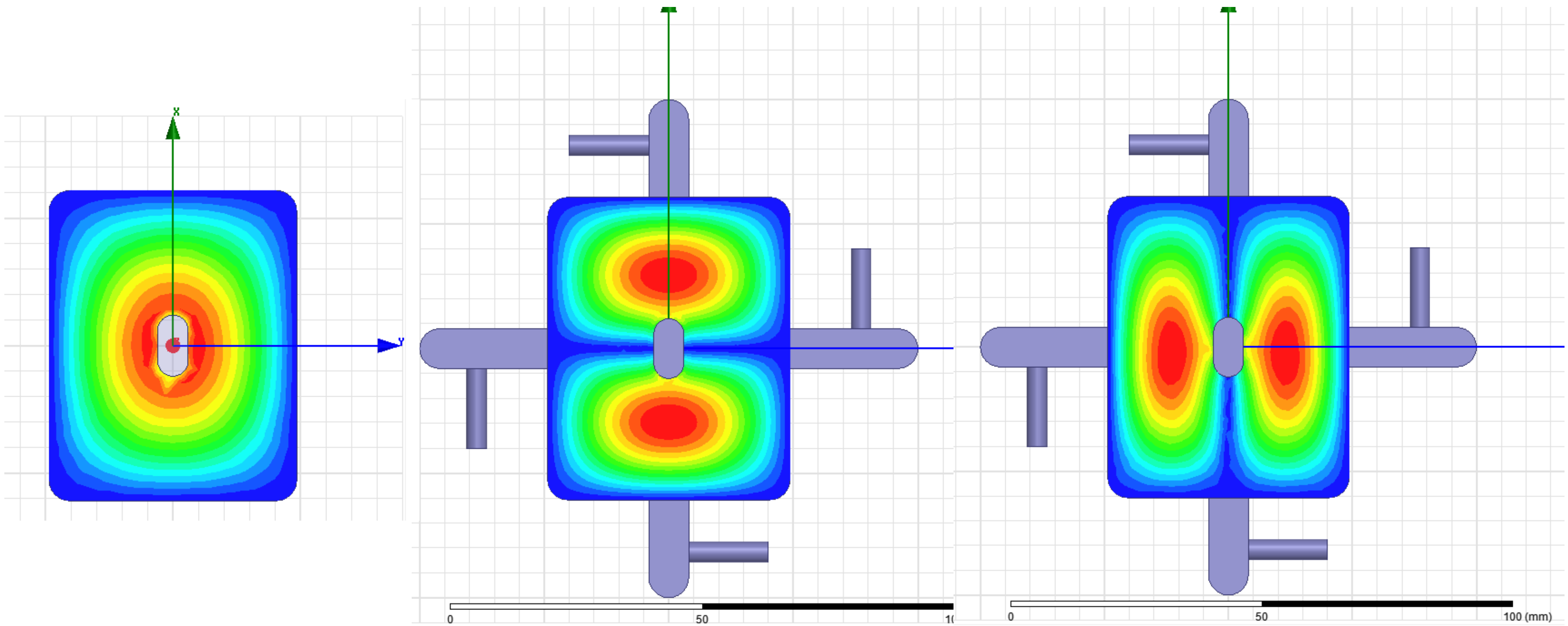
# 11cm Low-Q IP-BPM sensor cavity design

- Cavity dimensions for HFSS simulation



# 11cm Low-Q IP-BPM sensor cavity design

- Electric field mapping of HFSS simulation




Mono-pole mode
:3.9808 GHz

X-dipole mode
:5.7123 GHz

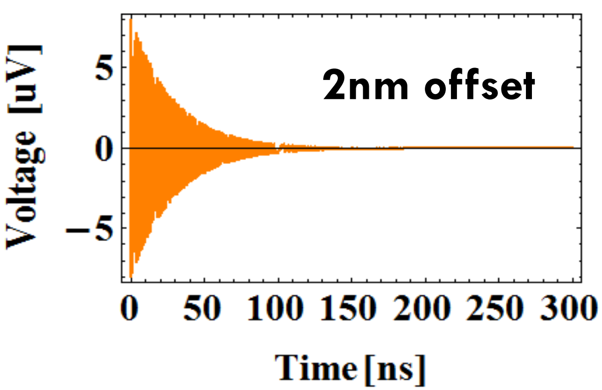
Y-dipole mode
: 6.4255 GHz

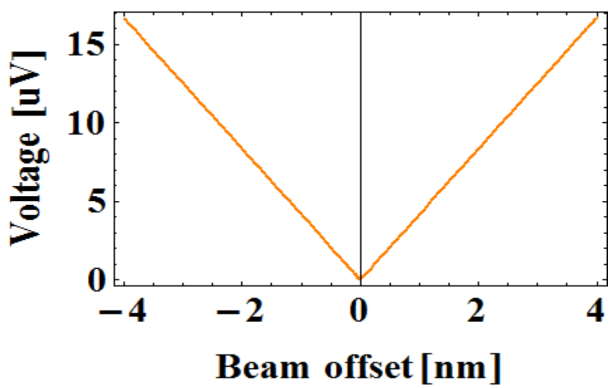
# Results of HFSS simulation

11cm AL ver.

| Port | $f_0$ (GHz) | β | $Q_0$ | $Q_{ext}$ | $Q_L$ | τ (ns) |
|---|---|---|---|---|---|---|
| X-port | 5.7127 | 5.684 | 4959.29 | 872.42 | 741.91 | 18.72 |
| Y-port | 6.4280 | 5.684 | 4670.43 | 821.61 | 698.70 | 17.23 |

Output signal for Y-port (11cm AL ver.)




| Parameter | Value | Unit |
|---|---|---|
| q (charge) | ~ 1.6 | nC |
| Beam energy | 1.3 | GeV |
| Bunch length | 8 | mm |

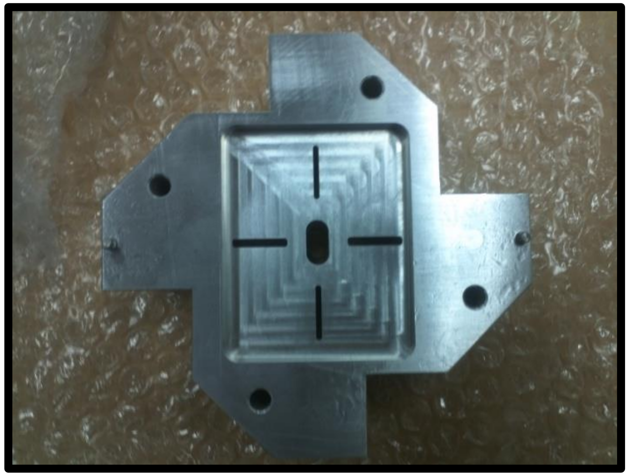
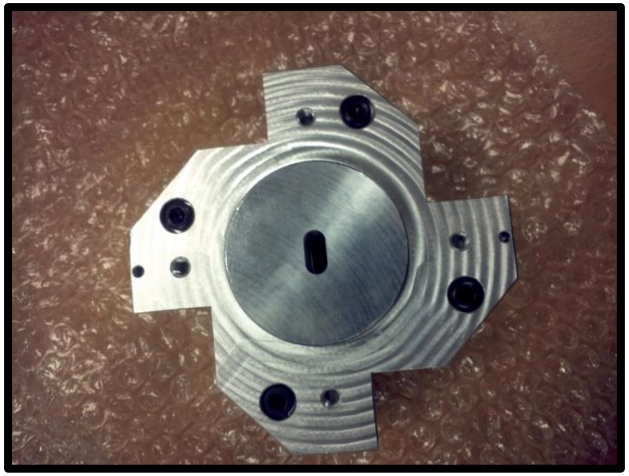
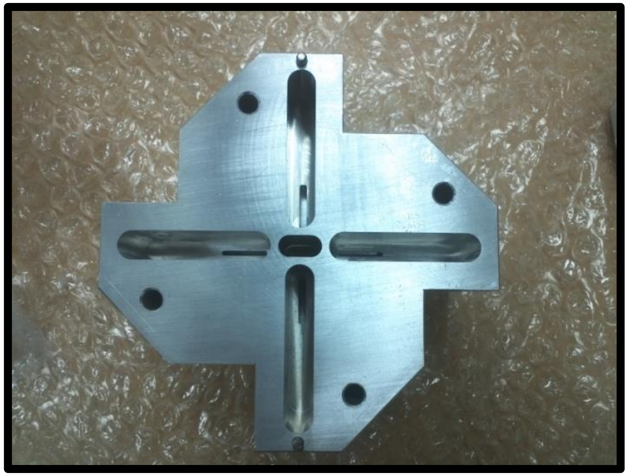
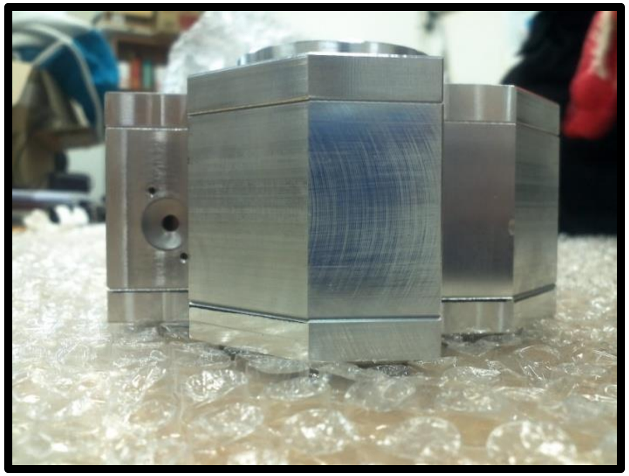
# RF measurement data

| | Port | $f_0$ (GHz) | β | $Q_0$ | $Q_{ext}$ | $Q_L$ | τ (ns) | V_out (uV/2nm) |
|---|---|---|---|---|---|---|---|---|
| Designed | X-port | 5.7127 | 5.684 | 4959.29 | 872.42 | 741.91 | 18.72 | 7.739 |
| Designed | Y-port | 6.4280 | 5.684 | 4670.43 | 821.61 | 698.70 | 17.23 | 7.448 |
| Double_1 | X-port | 5.6968 | 0.656 | 362.34 | 552.14 | 218.77 | 6.112 | 9.740 |
| Double_1 | Y-port | 6.4099 | 0.668 | 845.66 | 1266.7 | 507.11 | 12.59 | 6.010 |
| Double_2 | X-port | 5.6975 | 0.817 | 483.38 | 591.45 | 265.99 | 7.430 | 9.410 |
| Double_2 | Y-port | 6.4097 | 0.641 | 834.70 | 1302.5 | 508.70 | 12.63 | 5.927 |
| Single_1 | X-port | 5.6991 | [illegible] | [illegible] | [illegible] | [illegible] | 7.55[illegible] | 9.444 |
| Single_2 | Y-port | 6.4089 | [illegible] | [illegible] | [illegible] | [illegible] | 15.48 | 6.037 |

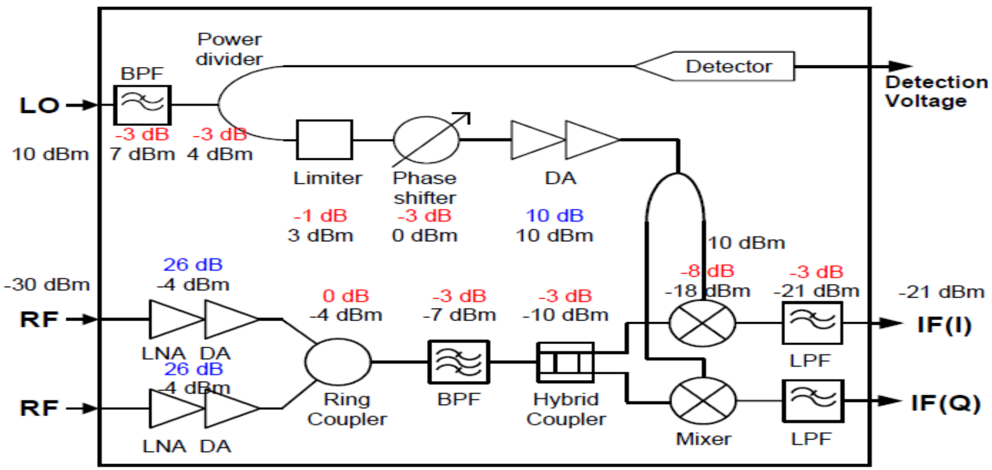
**The double block of IP-BPM was used for November beam test at the end of Linac.**

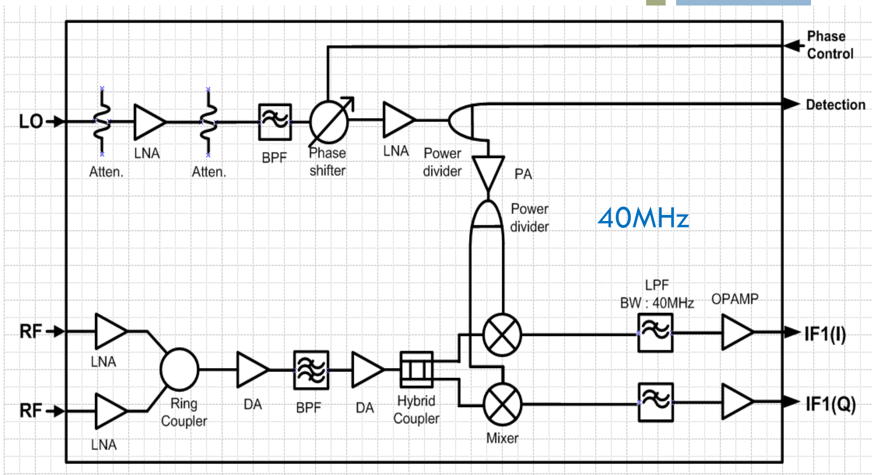
# Tested Double block IP-BPM

- **Made by Aluminum** (2kg for double block)

# What is new electronics?




- Conversion Gain : 10 dB
- Measured N.F

| Used devices | Measured N.F. |
|---|---|
| N.F. analyzer | 5 dB |
| S/G & S/A | 19 dB |

- BW of LPF : 50MHz

- Estimated position resolution

| N.F | Estimated Resolution |
|---|---|
| 0 dB | 3 nm |
| 5 dB | 4 nm |
| 19 dB | 20 nm |

- Measured Latency : 17ns

**What is new !?**

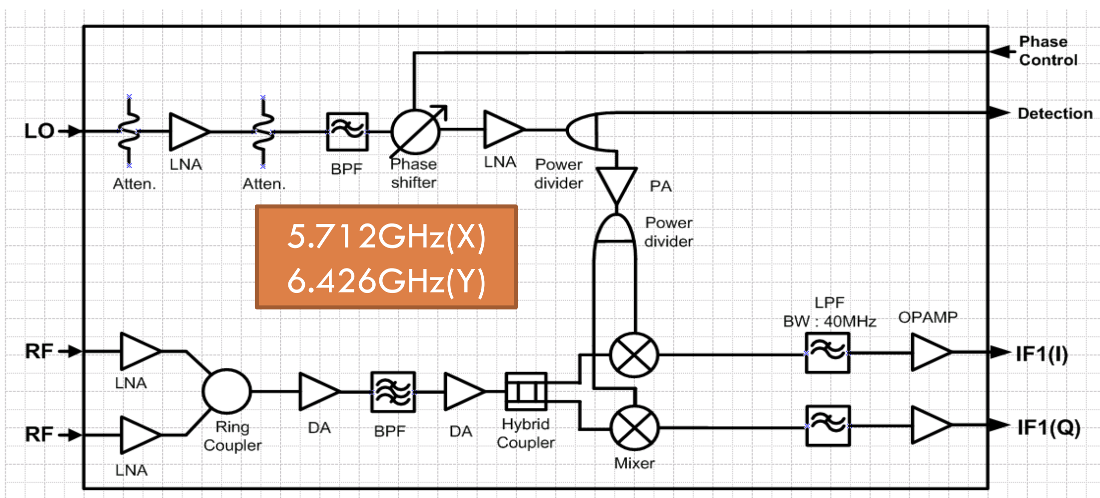
Total conversion gain: 10dB to 54dB

LPF: 50Mhz to 40Mhz

Phase shifter: Voltage type to Digital type

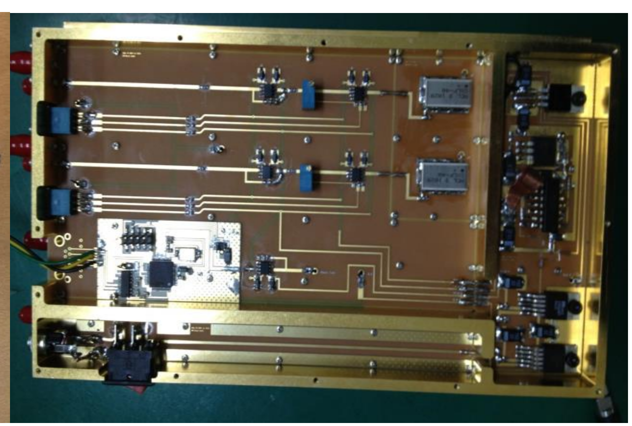
| | New electronics |
|---|---|
| BW of LPF | 40MHz |
| Gain | 54~44dB |
| Thermal Noise | -96.1dBm |
| Estimated Resolution due to thermal noise | 2nm |
| Cascaded NF | 1.88dB |
| RF $P1_{in}$dB | -22dB |
| Estimated Latency | 25ns |

# Simplified schematic of new electronics




Simplified schematic of the IP-BPM signal processing electronics.

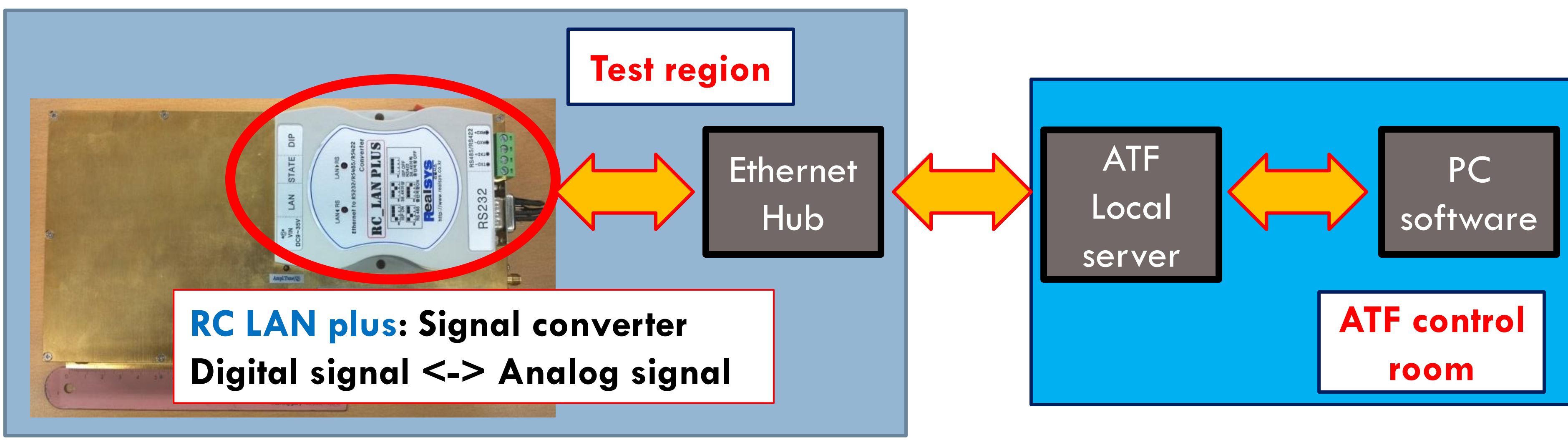
| | New electronics |
|---|---|
| BW of LPF | 40MHz |
| Gain | 54~44dB |
| Thermal Noise | -96.1dBm |
| Estimated Resolution due to thermal noise | 2nm |
| Cascaded NF | 1.88dB |
| RF $P1_{in}dB$ | -22dB |
| Estimated Latency | 25ns |

- Conversion Gain : 54~44dB(X,Y)
- Variable OPAMP: 10dB
- BW of LPF : 40MHz
- Cascaded N.F : 1.88dBdB
  - Remote phase shifter: 0 ~ 360 degree
  - Estimated position resolution : 2nm
  - Estimated Latency : 25ns

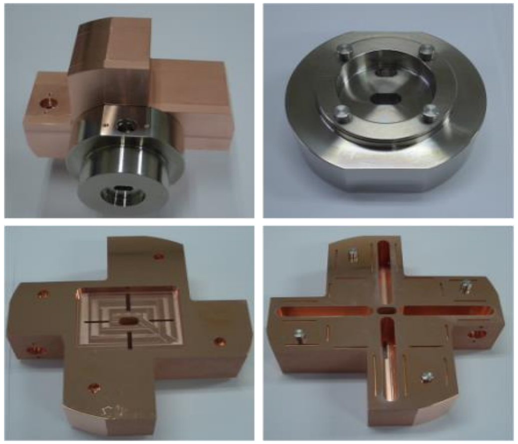
# Phase shifter remote control

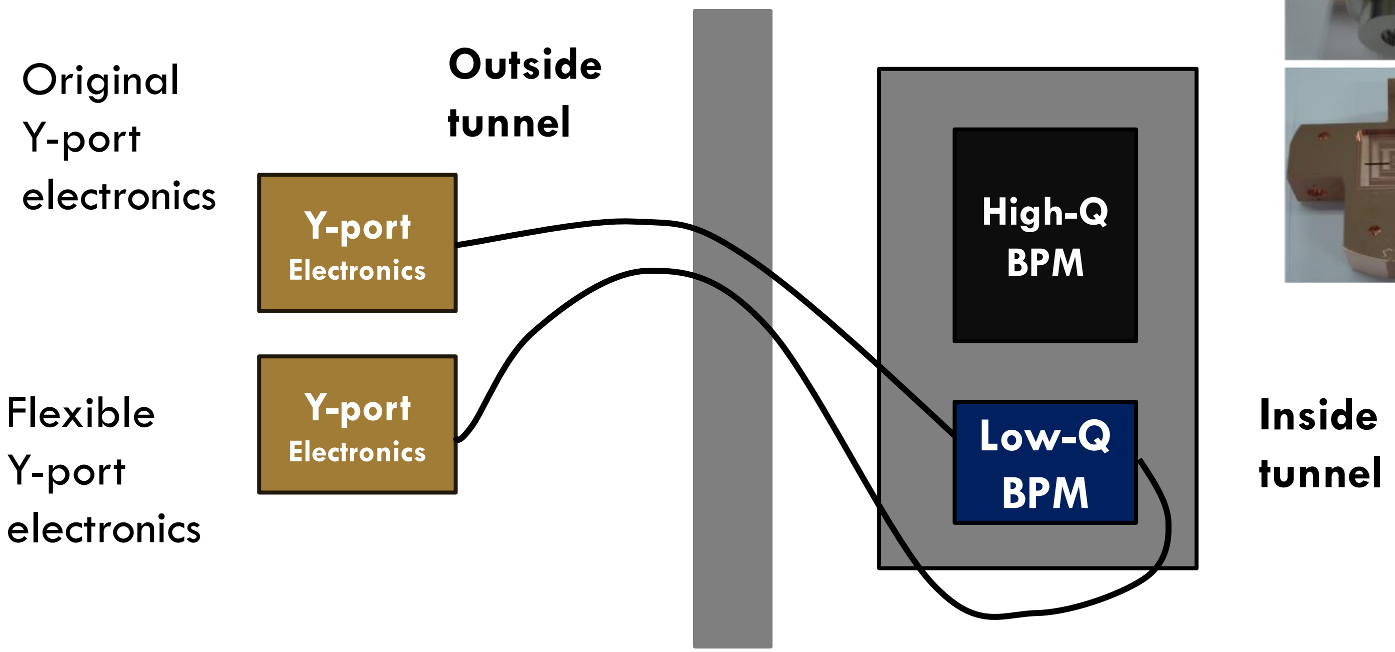
- In November beam test, the phase shifter was controlled remotely at the ATF control room.
- The phase shifter was connected to RC LAN plus to control due to digital signal. The LO signal phase was controlled from 0 degree to more than 360 degree.



# New Y-port electronics test (2012 Jan.)

- We tested two Y-port electronics at the same time by using one **old Low-Q IP-BPM** to check the performance of both electronics.
- Beam test scheme



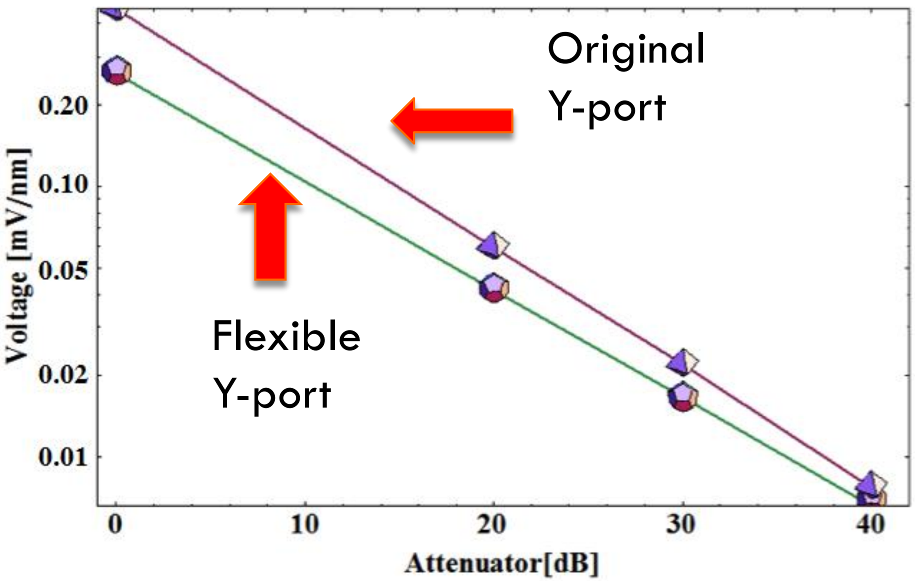


# Results of Electronics beam test

- Calibration slope for calibrating the I signal to actual beam position is summarized in Table.

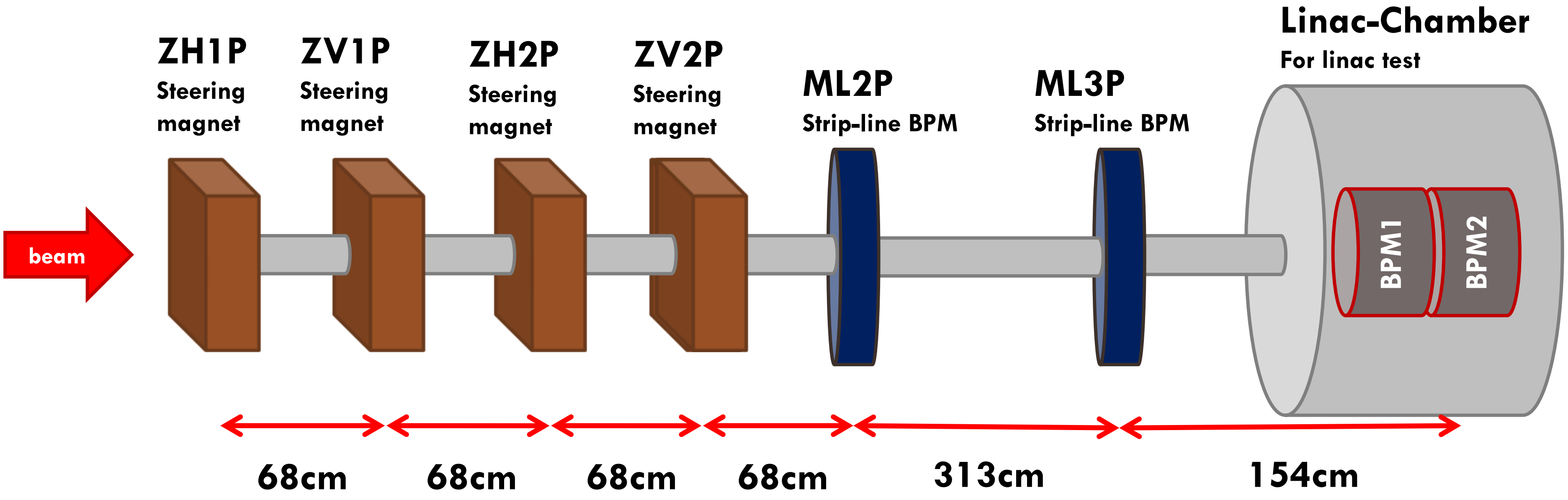
| [uV/nm] | w/o | 20dB | 30dB | 40dB |
|---|---|---|---|---|
| Y-port | 450.9 | 72.1 | 21.8 | 7.7 |
| Fx. Y-port | 263.2 | 41.6 | 16.3 | 6.3 |

**The results of calibration slope at the w/o att. case shows enough to measure 2nm resolution by using 14bit ADC.**
**(14bit ADC noise = 366uV)**
**450.9uV/nm= 3.7count/nm**
**263.2uV/nm=2.16count/nm**



# New IP-BPM Test scheme @ end of Linac

- Distance between each elements
  - In this test, we used two BPMs (Double block).
  - BPM sensitivity test performed during one shift
  - The beam position at Low-Q IP-BPM was estimated by using two strip-line BPMs.



# Results of IP-BPM y-port sensitivity At 2012 November beam test (w/o electronics)

- **IP-BPM sensitivity**

(For y-port)

= **2.2558**[uV/nm]

(one-port measurements of BPM1)

= **2.22996**[uV/nm]

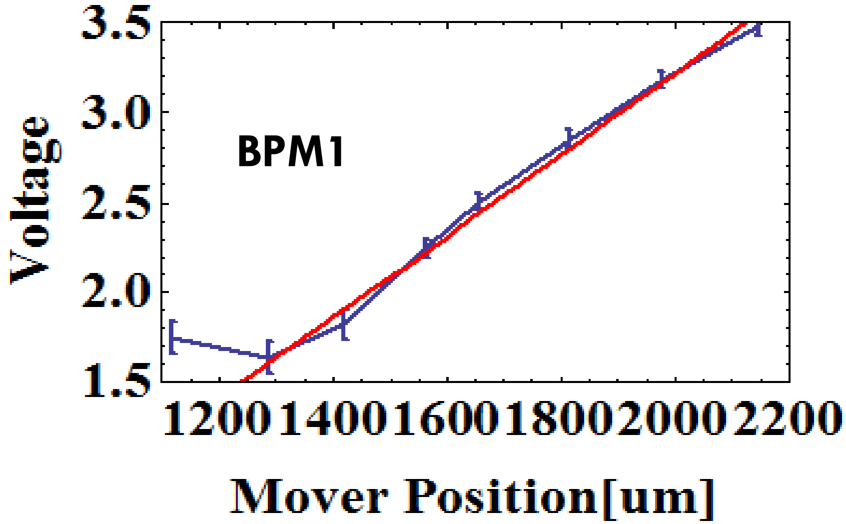
(one-port measurements of BPM2)

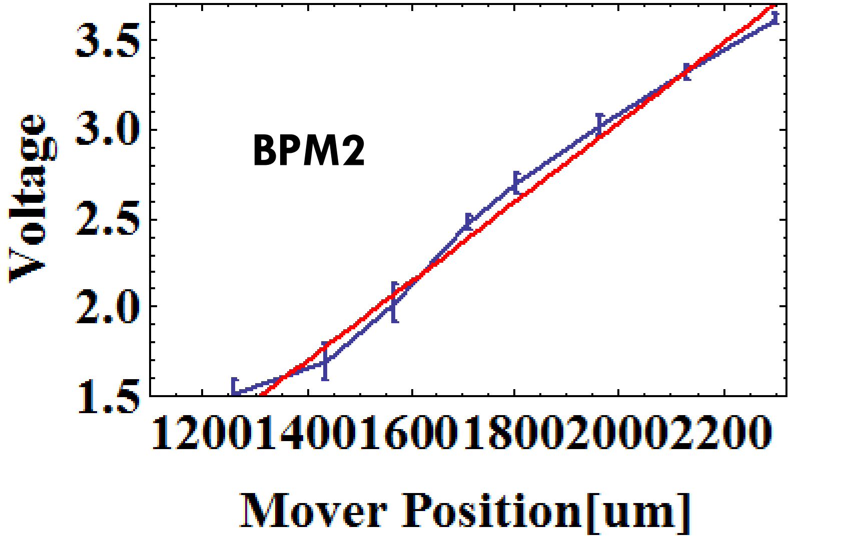
- **Designed sensitivity**

= **3.005** [uV/nm] (BPM1)

= **2.964** [uV/nm] (BPM2)

ICT monitor: 0.36~0.38 *10^10 (at LNE)



# Future plan

- IP-chamber will be installed at the IP-region with IP-BPMs.
- Reference cavity fabrication and sensitivity calibration.
- Electronics sensitivity check again with IP-chamber.
- BPM sensitivity check at the IP-region with piezo-mover.
- Final goal: 2nm beam position resolution measurement !

# Summary

- The low-Q IP-BPM was developed and tested at the ATF2. The old low-Q IP-BPM was achieved 70nm beam position resolution.

- New 11cm AL. low-Q IP-BPM was developed fabricated to install in the IP-chamber. Also, new electronics was developed to achieve 2nm beam position resolution with wide dynamic range The basic beam test was performed at the end of Linear accelerator in ATF2.

- Beam position resolution measurements for new IP-BPMs will be perform during 2013.

- Finally, the IP-BPM will be used for feedback system study with 2nm beam position resolution.

# Thank you for your attention!