KOREA UNIVERSITY

2022 가속기 및 빔 라인 미래인재
양성 교육단 여름학교

4GSR Beam Diagnostics

Korea University
Siwon Jang

Accelerator facility in the world

Storage ring and free-electron laser x-ray light sources of the world.

Source: APS Science 2014 (https://doi.org/10.2172/1224995)

Accelerator facility in the world

일본 KEK 가속기 연구소

4th Light Source & Collider, Acc. Test facility

3rd & 4th Generation Light Source

미국 방사광 가속기
ALS at LBNL

PLS-II
PAL XFEL
4GSR

ATF2
KEK-B
PF

Accelerators in the world

LHC
J-Parc
KEK-B

Proton Accelerator

RAON
FRIB
RCNP
RIKKEN

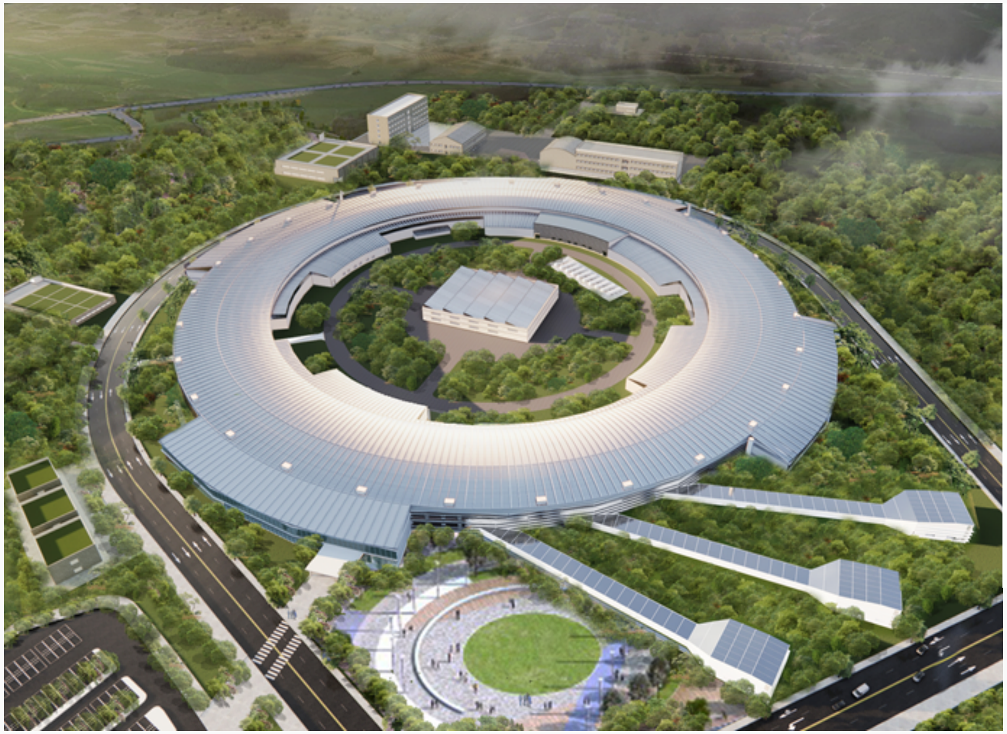
Heavy Ion Accelerator

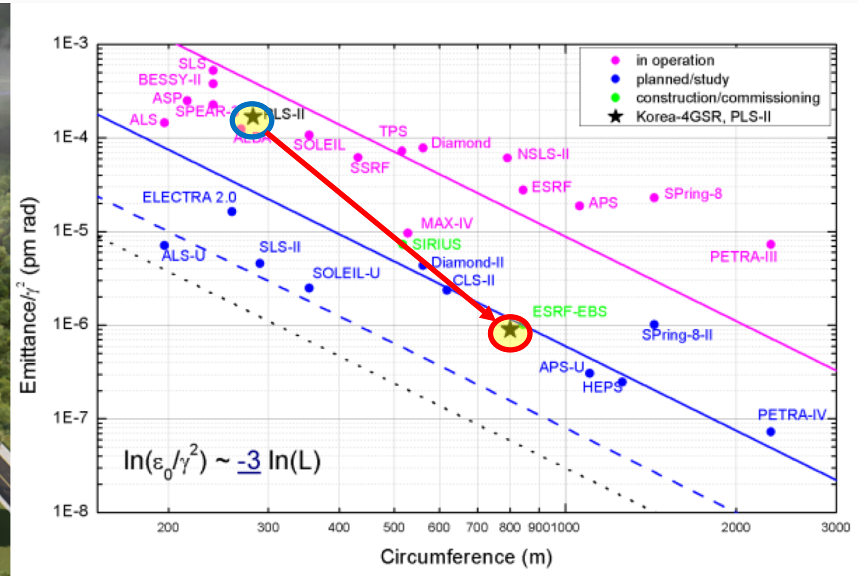
중이온 가속기

일본 양성자 가속기 J-PARC

Accelerator facility in the world

4GSR project of Korea at Ochang





PLS-II 포항 방사광 가속기 대비
100배 성능 향상 기대

High brilliance ⇨ Small beam size

⇨ Precise & stable orbit control (sub μm resolution)

" For the fourth generation storage ring, it's more precise, more accurate, and fast processing beam diagnostic devices are required.

Introduction

- **가속기 연구 개발 또는 빔 진단 장치 연구?**
- **방대한 연구 주제 – 광대한 복합 연구 개발 기술이 요구 됨**
- **필요한 연구 분야 및 관련성:**
  - Accelerator physics – particle physics – RF technology – optics – mechanics – electronics – software engineering – …
- **극한의 연구 환경:**
  - Radiation (SEE, radiation ageing, activation)
  - Many sources of measurement noise and background
    - Place readout close to detector, but -> radiation
  - RF heating by the beam
  - Accessibility and maintenance
  - Sometimes: cryogenic temperatures
  - Mostly: must operate in vacuum and be UHV compatible

Introduction

- **가속기 빔 진단 장치의 필요성:**
  - **빔 운전을 보조하는 시스템이며, 가속기 튜닝 및 운전에 사용되고 전체 시스템의 성능 향상을 위한 장치이다.**

- **빔 진단 장치 개발을 위한 고려:**
  - **선형가속기 및 전송라인**: Single pass ↔ **저장링**: multi pass
  - **전자:** almost relativistic (**β**~1) ↔ **양성자/중이온**: non-relativistic for Ekin < 1 GeV/u
  - **전체 빔 에너지** (beam particles x particle energy) low ↔ high
  - **다양한 주파수 대역**
  - **DC beam or bunched beam additionally fill pattern**
  - **Non-intercepting ↔ Intercepting ↔ Destructive**

- **무엇을 배울 것인가?**
  - **왜 빔 진단 장치가 필요한가?**
  - **가속기의 대표적인 5가지 빔 진단 파라미터 및 대응되는 주요 장치**
  - **빔 위치 모니터 및 일렉트로닉스의 원리**
  - ****Cavity BPM의 개발부터 측정까지**

가속기 연구의 이상과 현실 사이...?

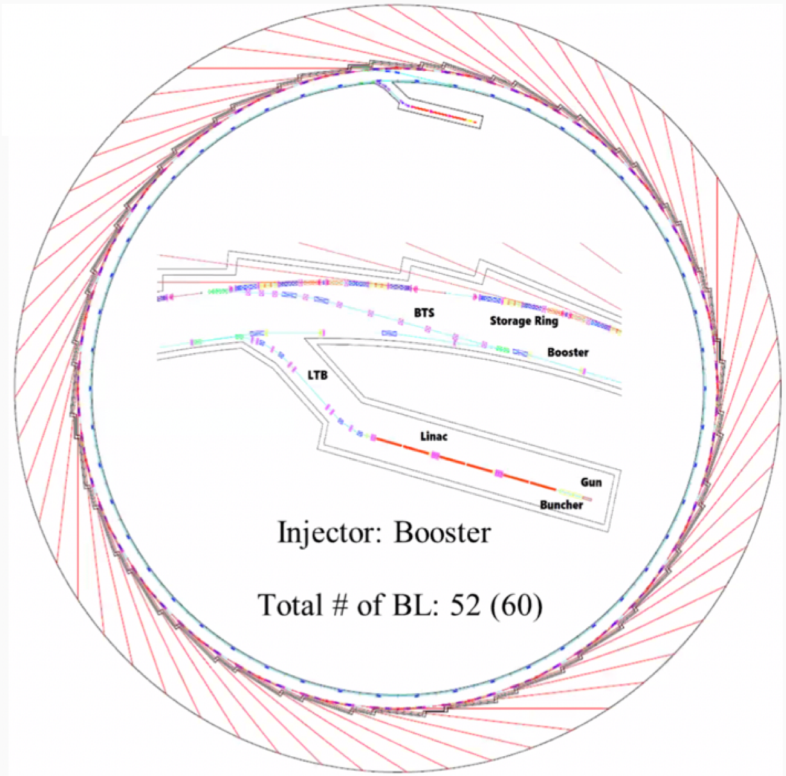
- *왜 가속기는 설계한 대로 동작하지 않는가?*

- *왜 빔 진단 장치가 필요하지?*

- *왜 가속기가 발전함에 따라 더욱 많은 빔 진단 장치가 요구되는가?*

가속기 연구의 이상과 현실 사이...?

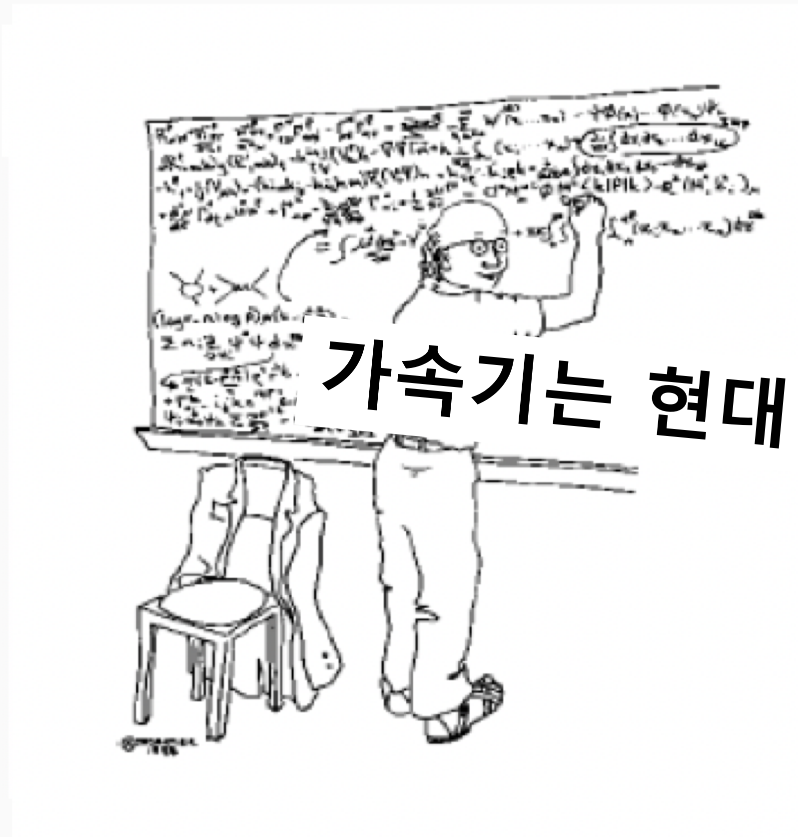
4GSR 방사광 가속기의 구성도



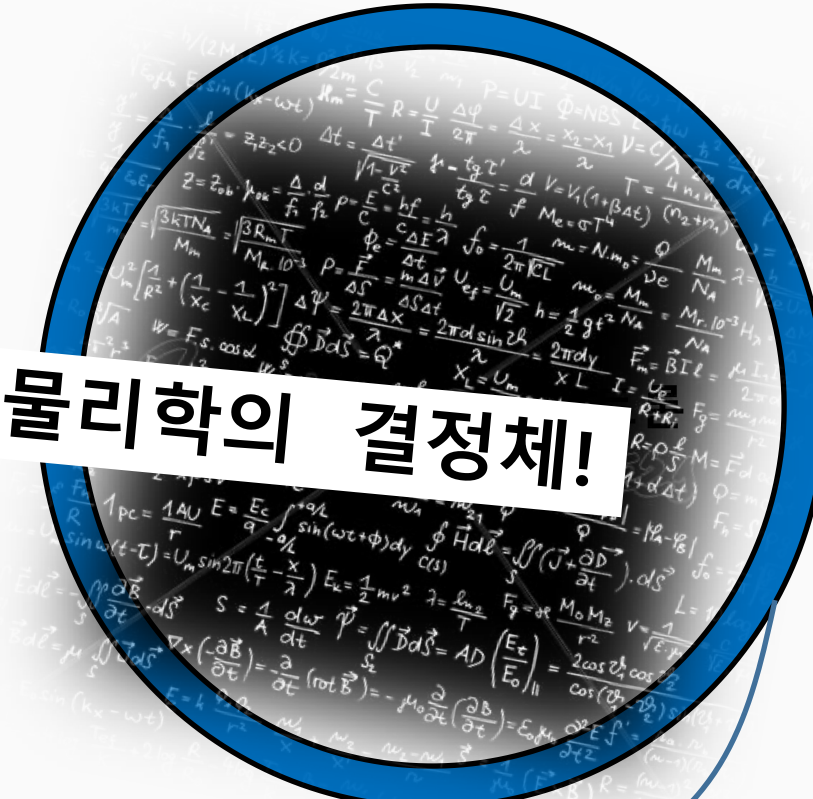
일반 적인 가속기의 구성도

가속기 연구의 이상과 현실 사이...?

4GSR 방사광 가속기의 구성도



일반 적인 가속기의 구성도



가속기는 현대 물리학의 결정체!

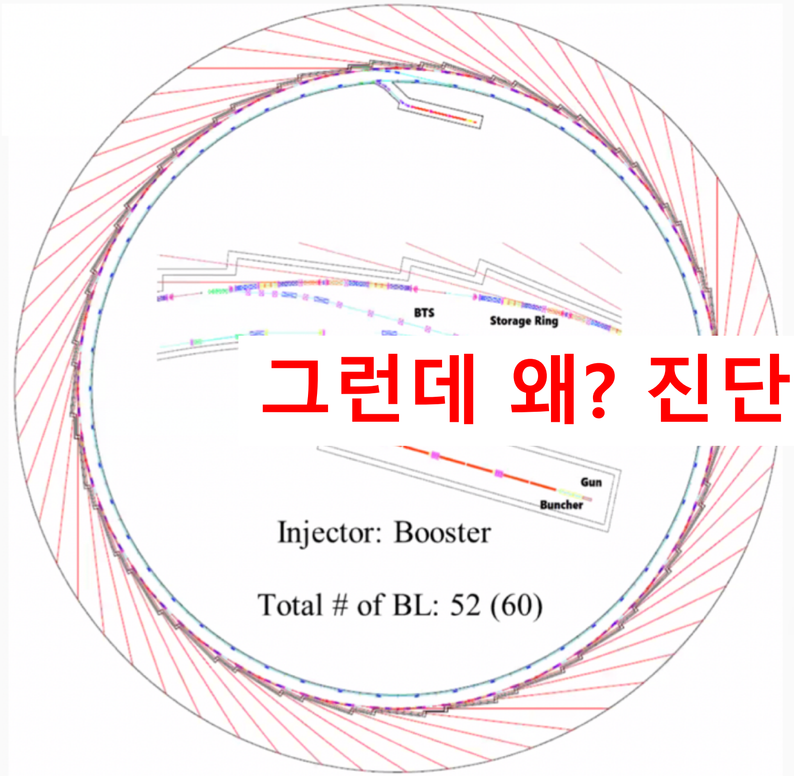
RF gun

선형가속기

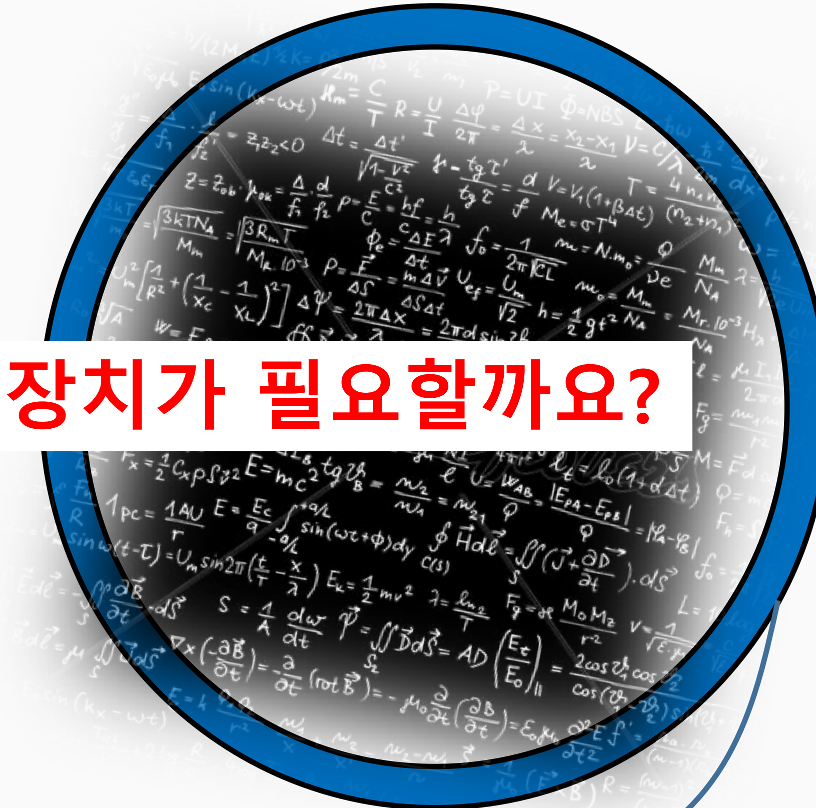
전송라인

가속기 연구의 이상과 현실 사이...?

4GSR 방사광 가속기의 구성도



일반 적인 가속기의 구성도



그런데 왜? 진단 장치가 필요할까요?

RF gun

선형가속기

전송라인

가속기 연구의 이상과 현실 사이...?

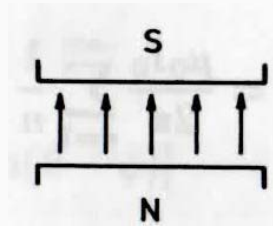
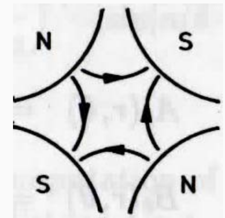
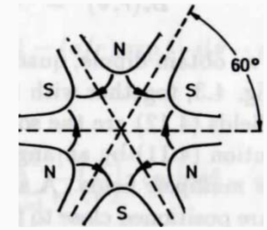
빔 진단 장치가 필요한 6가지 대표적인 이유!

- ***Component tolerances and related random errors***
- ***Environmental effects***
- *Equipment fault*
- *Equipment set-up*
- *Performance tuning and preservation*
- ***Stupid things (Human error)***

Component tolerances and related random errors

- Finite precision of survey and alignment
- Finite accuracy of power supplies
- Ripple of power supply
- Finite accuracy of magnet field measurement
- Ripple of RF Amplitude
- RF phase noise
- Drifts (temperature, humidity, aging of component)

Component tolerances and related random errors

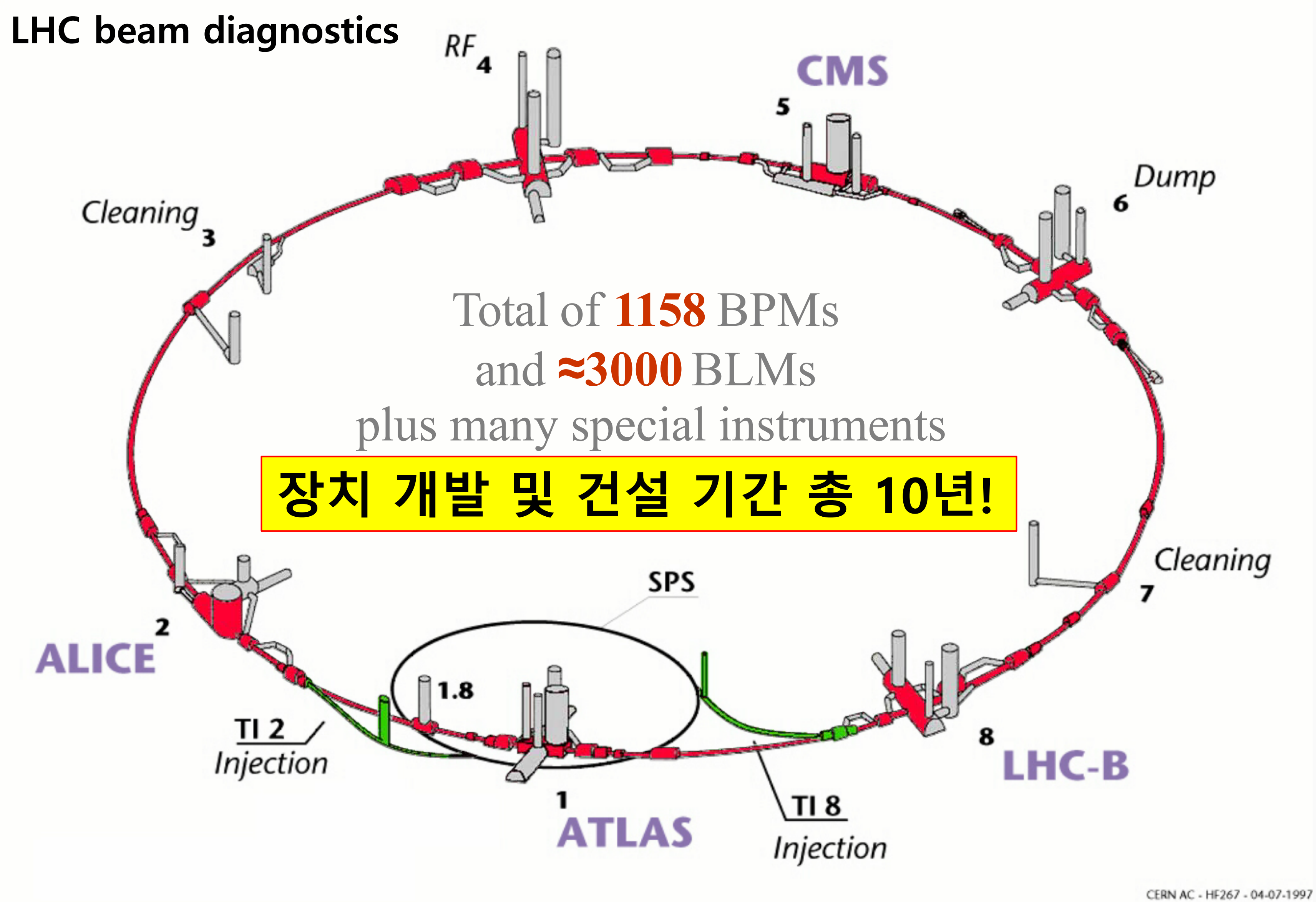
	Dipole	Quadrupole	Sextupole
			
purpose	beam deflection & sometimes focusing	beam focusing	chromatic correction
unwanted, but some how predictable side effects	sextupole component modifies chromaticity reduces acceptance	dodecapole component (usually negligible)	limits dynamic acceptance
effect of excitation errors and ripple	generates orbit errors and chromaticity deviations	generate tune errors	generate chromaticity errors
most critical alignment issues	roll angle generates vertical orbit excursions and spurious vertical dispersion	transverse shifts generate orbit excursions and spurious dispersion roll angle generates x, y coupling vertical shift destroys beam polarisation	vertical displacement generates x,y coupling horizonal displacement generates tuneshift

Environmental effects

- **Subsiding of building(PLSII…)/tunnel foundation**
- Mechanical vibrations induced by water flow, vacuum pumps, water pumps, ventilation
- Mechanical vibrations from nearby traffic or construction work
- **Earth quake vibrations (KEK, J-PARC in JAPAN)**
- Earth magnetic field
- Magnetic fields from electric currents induced on vacuum chamber
- Stray fields from permanent magnets in vacuum pumps and vacuum gauges
- Field distortions from magnetic materials in support structures, building and equipment
- Magnetic stray field from cables

Stupid things (Human error)

LHC beam diagnostics



Stupid things (Human error)

Stupid things !

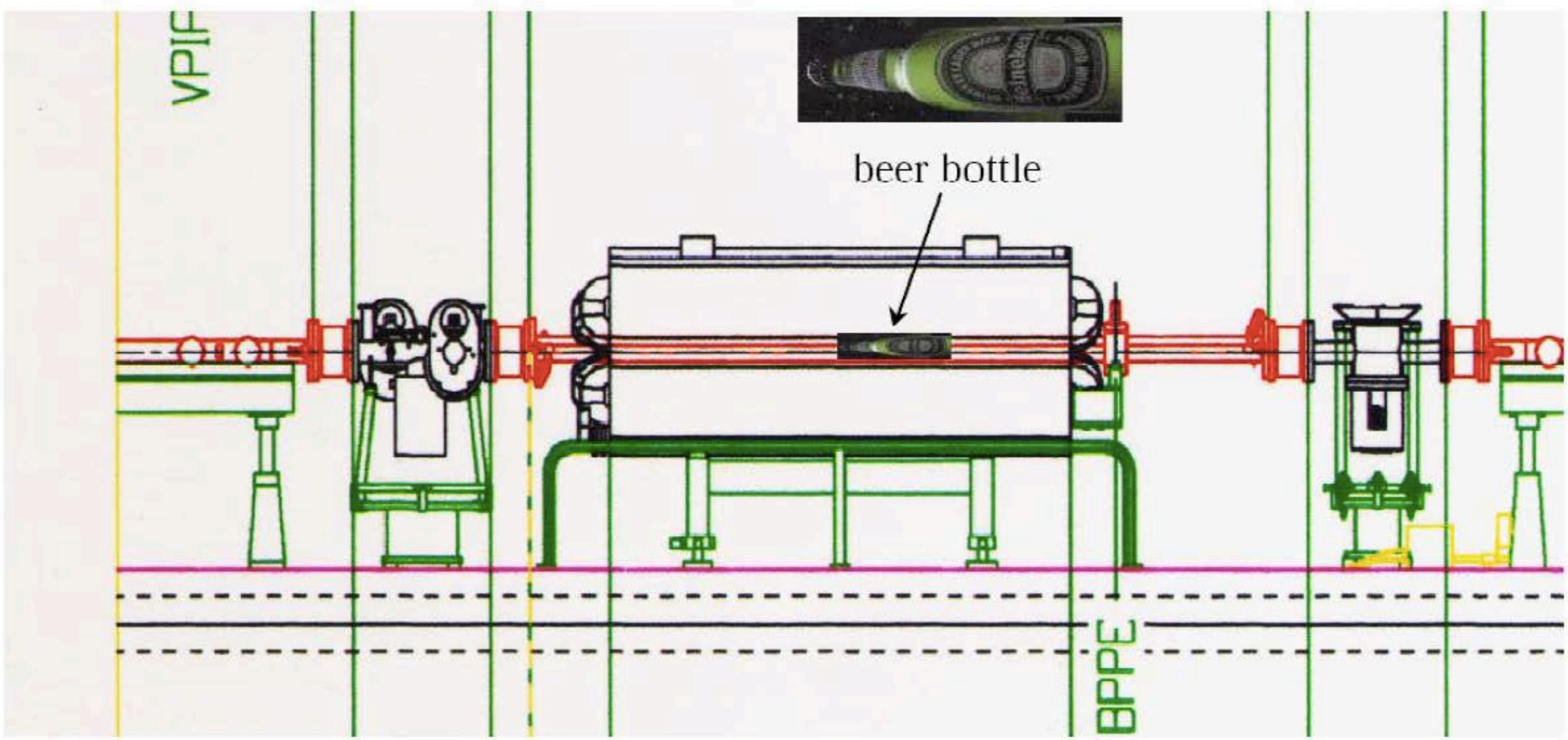
- ☹ magnets connected with wrong polarity
- ☹ cables connected to wrong equipment
- ☹ wrong entries in control system database
- ☹ calibration values mixed up
- ☹ "nominal settings" from wrong optics file
- ☹ kicker mounted in wrong direction
- ☹ somebody stepped on beampipe to change neon tube
- ☹ beer bottles in vacuum chamber
- ☹ …

Stupid things (Human error)

Stupid things !

True or False?

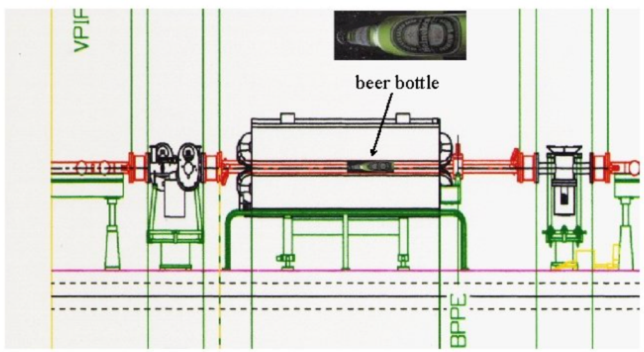
http://blogs.nature.com/news/2009/11_a_tale_of_two_beer_bottles_1.html



Stupid things (Human error)

Stupid things !

Zoom sur Quadrupole

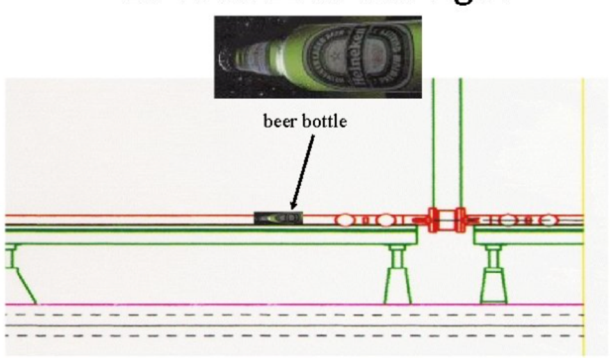


28th November 2019, CERN S Myers LEP 30 Colloquium 52

Zoom sur Quadrupole beer bottle 28 th November 2019, CERN S. Myers LEP 30 Colloquium 52

True !!

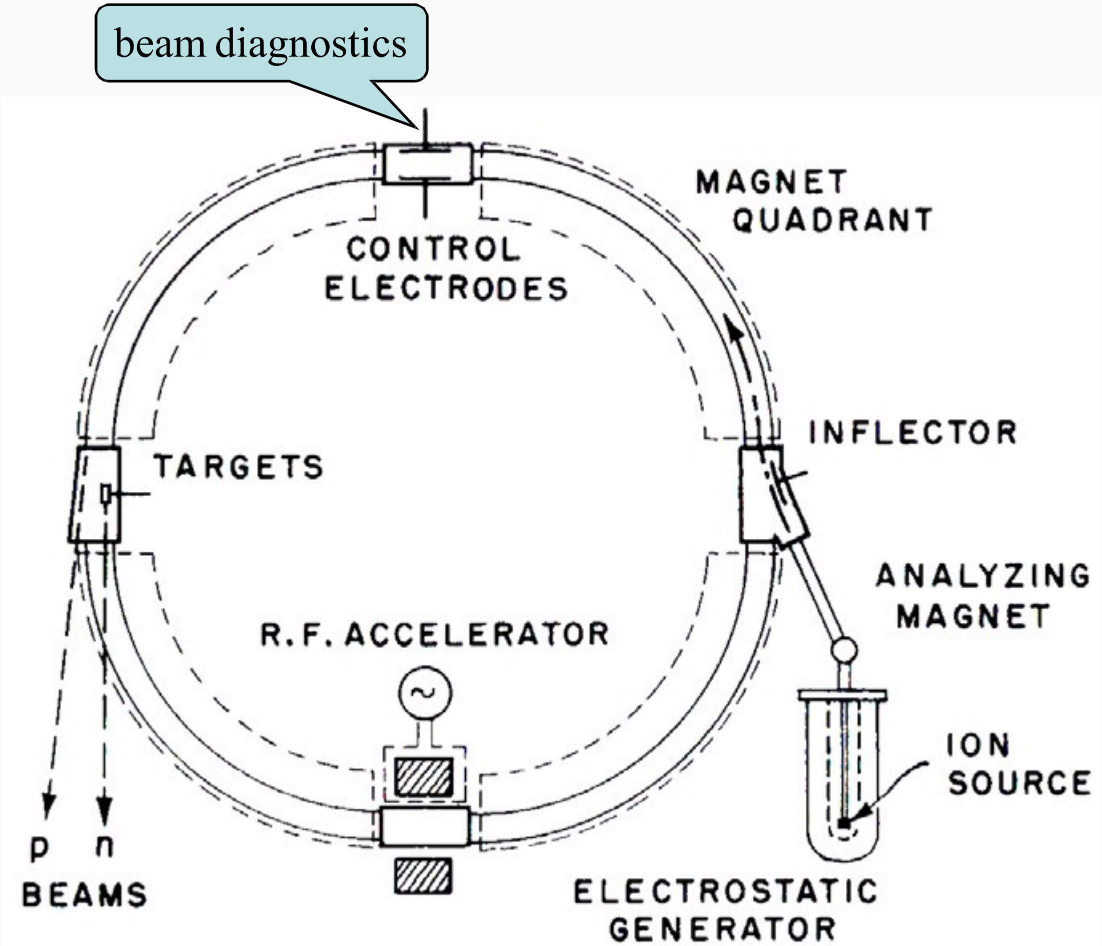
10 metres to the right



Unsociable sabotage: both bottles were empty!!

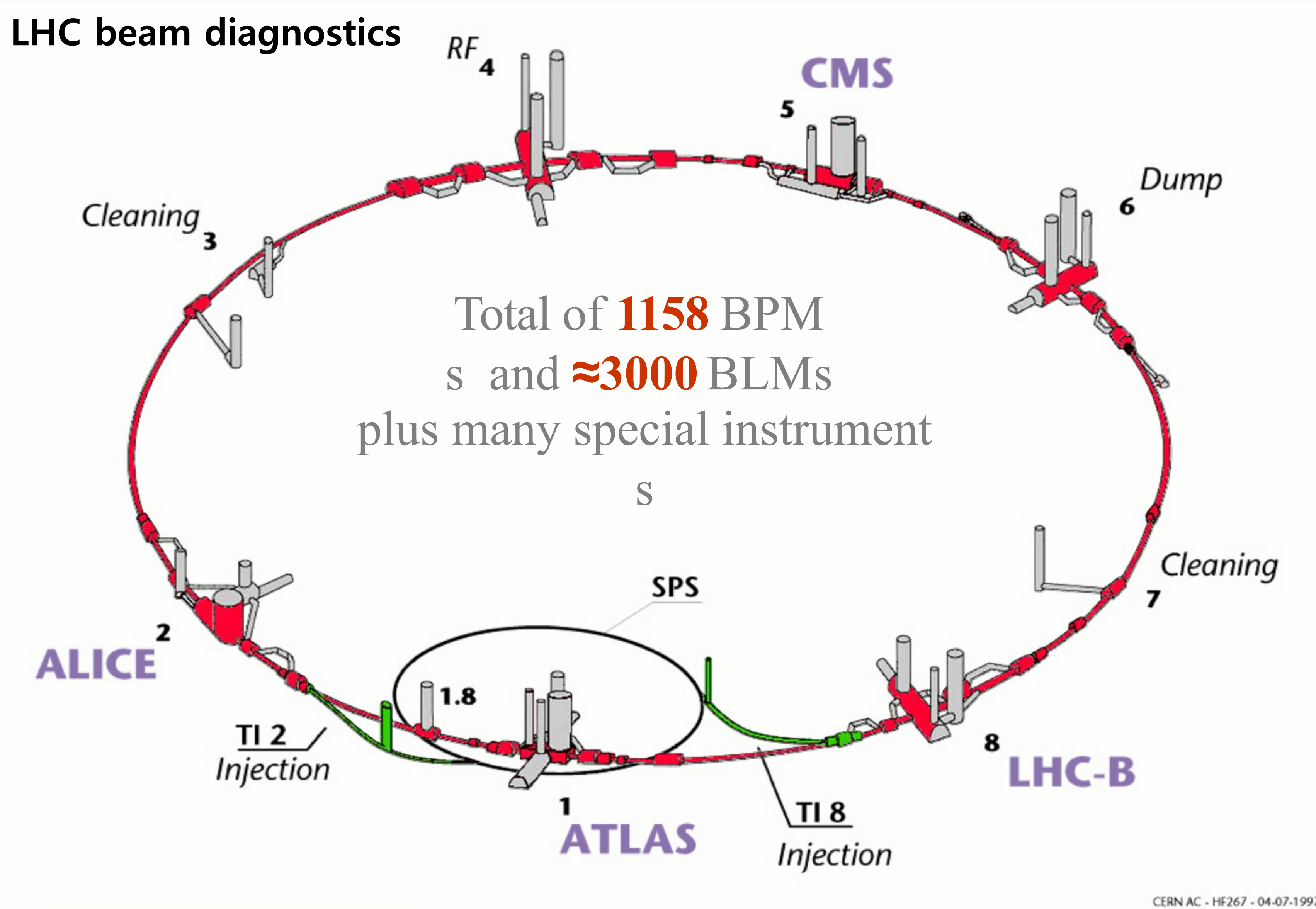
10 metres to the right beer bottle Unsociable sabotage: both bottles were empty!! 28 th November 2019, CERN S. Myers LEP 30 Colloquium 53

Beam diagnostics, how much ?



Layout of an early proton synchrotron

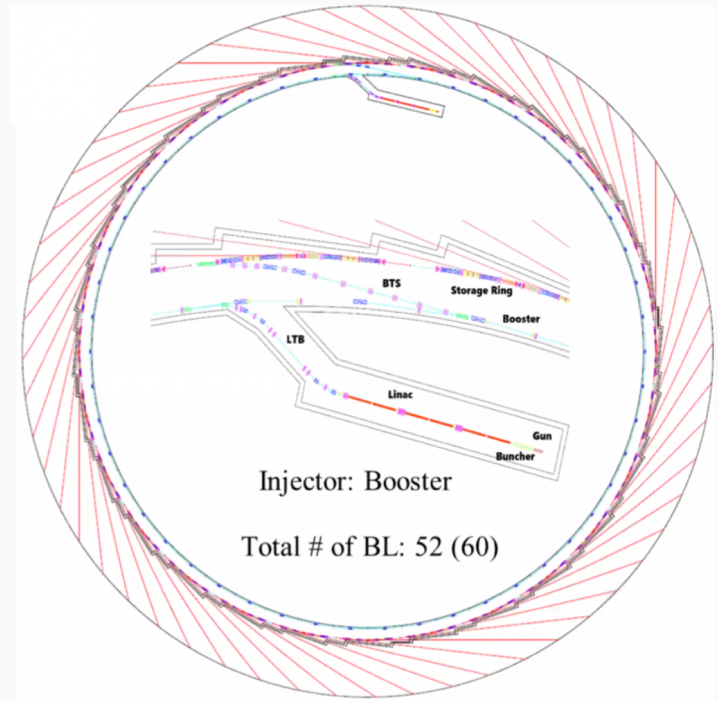
Beam diagnostics, how much ?



Beam diagnostics, how much ?

- 4GSR 방사광 가속기 빔 진단 장치

	분 류	측 정	셀별 개수				
			(1)	(2)	(3)	(4)	(5)
1	BPM (BTN, STRL)	Beam Position	3*	5*	50	6*	280
2	BPRM (YAG/OTR)	2D Profile, Emit., Energy	5	6		7	
3	SX Diag. Hutch	Beam Size, Emit.					1
4	VL Diag. Hutch	Beam Size, Emit., Bunch					1
5	Compact VL IF	Beam Size, Emittance			5		28
6	Turbo ICT (AC)	Beam Current	2	1		1	
7	NPCT (DC)	Beam Current			1		1
8	FPM	Filling Pattern Monitor					1
9	Streak Camera	Bunch Profile, Pattern					1
10	New XBPM	Photon Beam Position					20
11	BLM	Beam Loss	1		5		28
12	E Meas.	Beam Energy (spin)			1		1
13	Tune Meas.	Tune			1		1
셀별 총 진단장치 개수			11	12	63	14	363

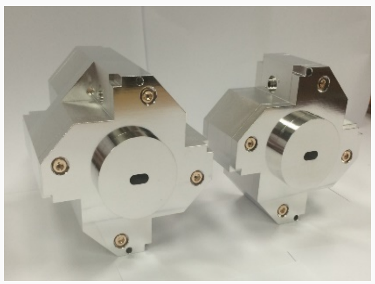


(1) LINAC, (2) LTB(Linac To Booster), (3) BOOSTER RING, (4) BTS(Beam Transport System), (5) STORAGE RING
* Single-pass 빔라인은 Button (BTN) Type 대신 Strip-line (STRL) Type BPM을 사용한다.

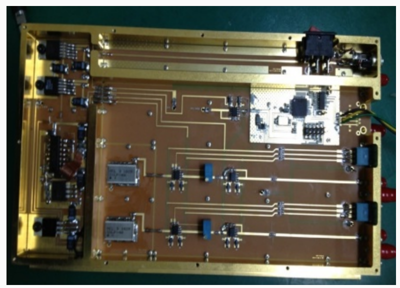
4GSR beam diagnostics

5가지 대표적인 빔 파라미터 및 대응 빔 진단 장치!

- 빔 위치 (Beam Position) ⬄ 빔 위치 모니터(Beam Position Monitor)
  - 궤도, 격자구조 변수들, 튠, 색수차, 빔 궤도 보정,…



Cavity BPM

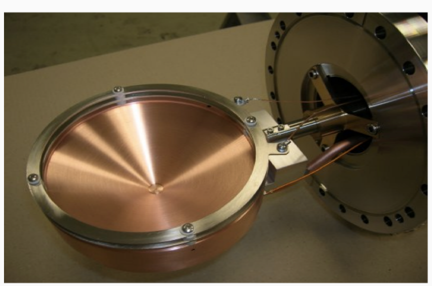


Cavity BPM electronics

Button BPM

Button BPM electronics

- 빔 세기 (Beam Intensity) ⬄ 빔 전류 모니터 (Beam Current Monitor)
  - DC & 빔 번치 전류, 빔 번치 라이프타임 , 번치 효율,…



Faraday cup

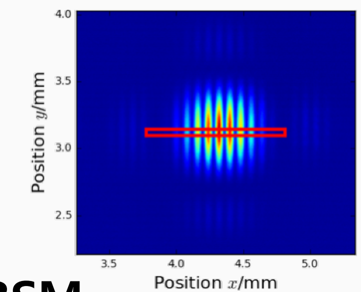
DCCT

ACCT

4GSR beam diagnostics

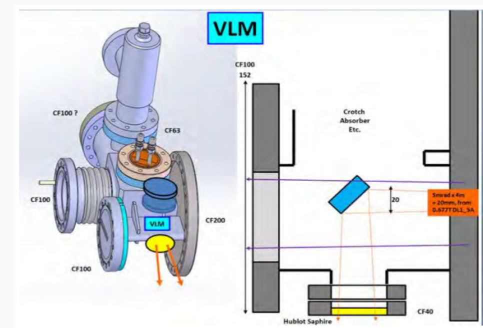
5가지 대표적인 빔 파라미터 및 대응 빔 진단 장치!

- 빔 분포 (Beam Distribution) ⇔
  빔 분포 모니터 (Beam Profile Monitor)
  수직 수평방향 및 길이 방향 빔 분포, 에미턴스,…



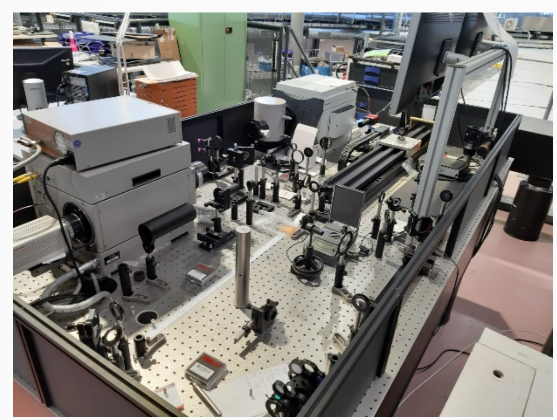
IBSM

- 빔 손실 (Beam loss) ⇔
  빔 전류 모니터 (Beam loss Monitor)
  DC & 빔 번치 전류, 빔 번치 라이프타임 , 번치 효율,…



VLM

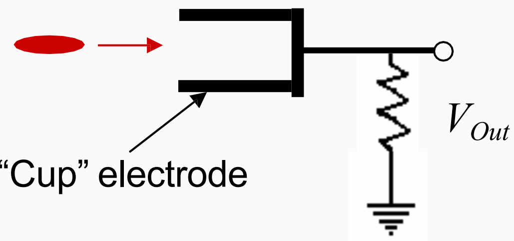
- 빔 에너지 (Beam Energy) ⇔
  빔 에너지 모니터 (Beam Energy Monitor)
  선형가속기 및 저장링 빔 에너지 측정,…

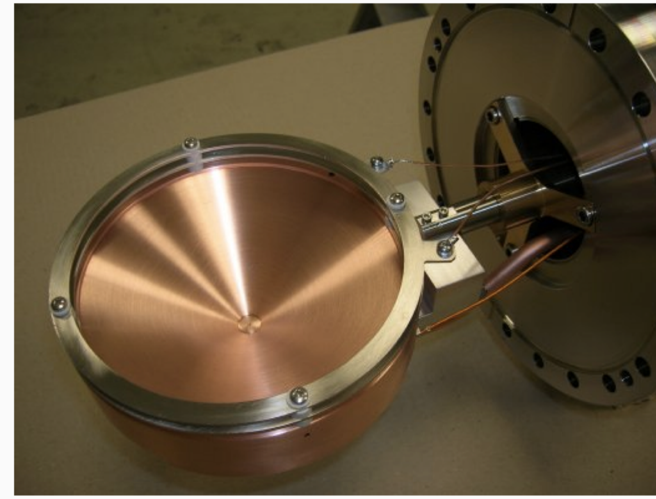


Bunch Length Monitor

Current and Transmission

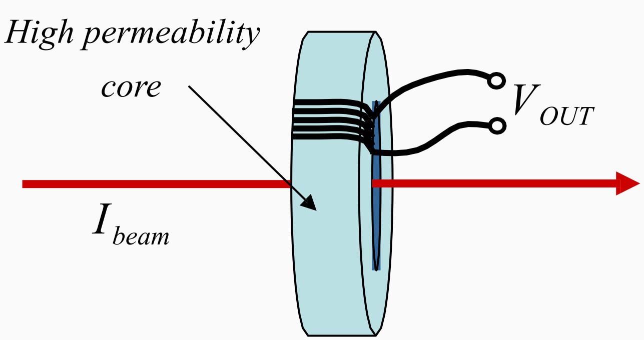
- destructive: Faraday cup

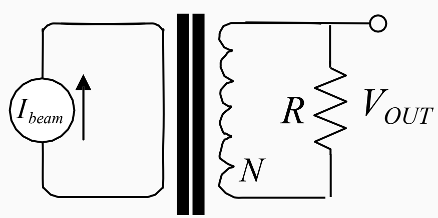




  - low energy particles stopped in material (→ Bethe Bloch)
  - very low intensities (down to 1 pA) can be measured

- non destructive: current transformer
  - beam acts as single turn pimary winding of transformer
  - measuring AC component of beam current





Current and Transmission

Transformer: **→ measurement of the beam's magnetic field**

- Magnetic field is guided by a high μ toroid
- **Types:** FCT → large bandwidth, $I_{min} \approx$ 30 μA, BW = 10 kHz ... 500 MHz

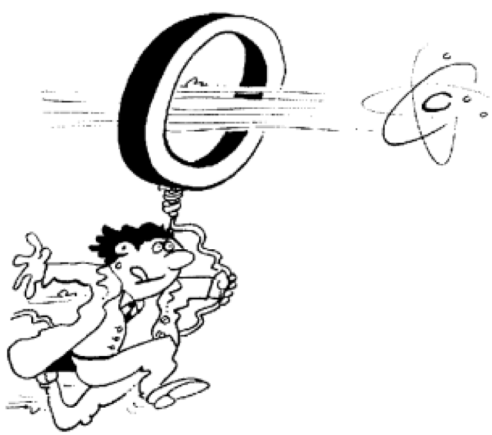
  [ACT : $I_{min} \approx$ 0.3 μA, BW = 10 Hz .... 1 MHz, used at proton LINACs]

  DCCT: two toroids + modulation, $I_{min} \approx$ 1 μA, BW = dc ... 20 kHz
- non-destructive, used for all beams

Faraday cup: **→ measurement of beam's charge,**

- low threshold by I/U-converter: I_{beam} > 10 pA
- totally destructive, used for low energy beams only

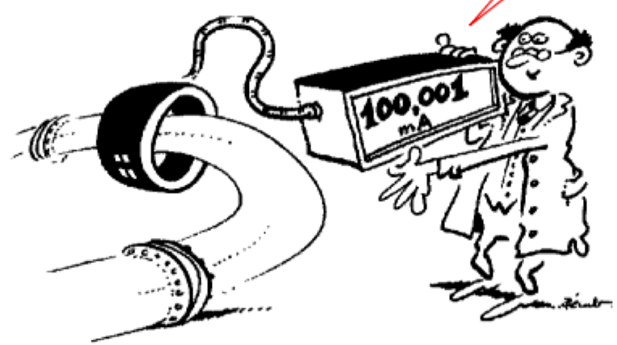
Fast Transformer FCT



Active transformer ACT

DC transformer DCCT

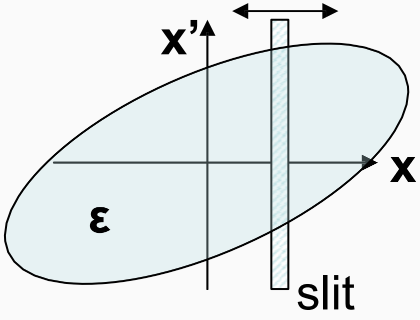
Resolution limit

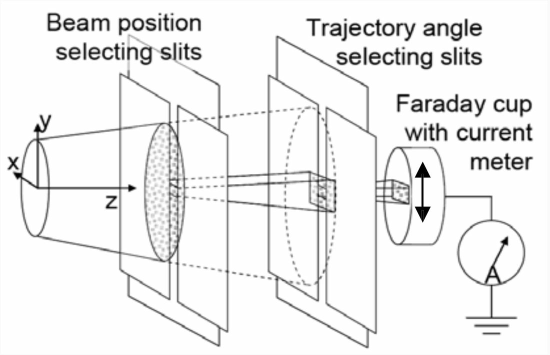


Company Bergoz

Transverse Emittance

- principle
  - slit produces vertical slice in transverse phase space
  - measure intensity as function of **x'**
  - moving of slit → scan of phase space (N_x x $N_{x'}$ measurements)



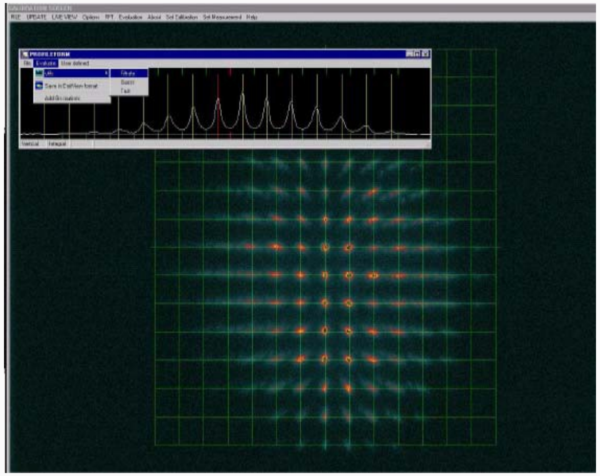


M.P.Stockli, Proc. BIW 2006, p.25

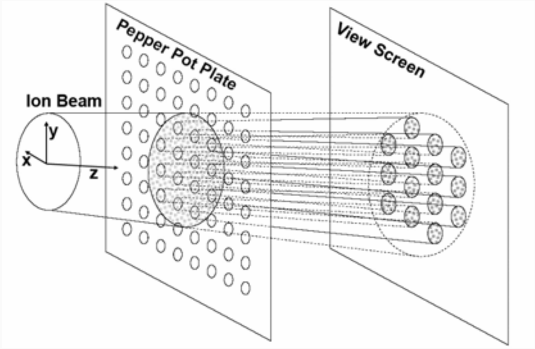
- monitor with **x'** resolution instead of scan:

  SEM, profile grid,…

  → N_x measurements



- 2-dimensional extension: Pepper pot



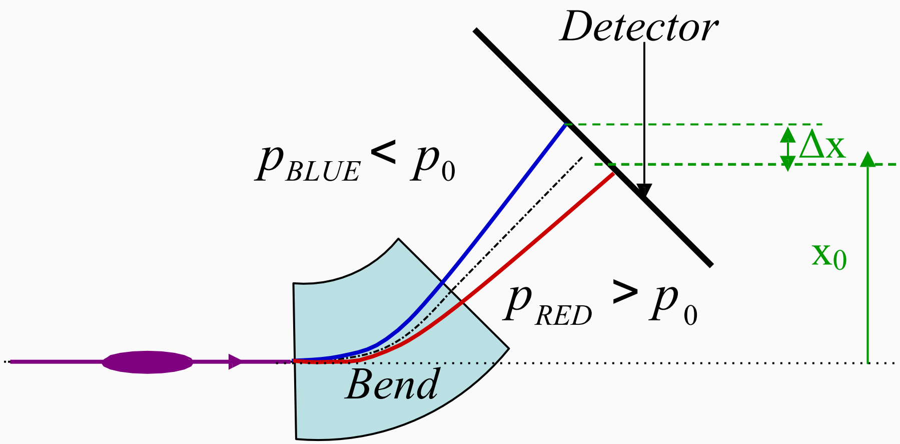
P.Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS 2006

→ 1 measurement

N_x x $N_{x'}$ holes

Longitudinal Plane

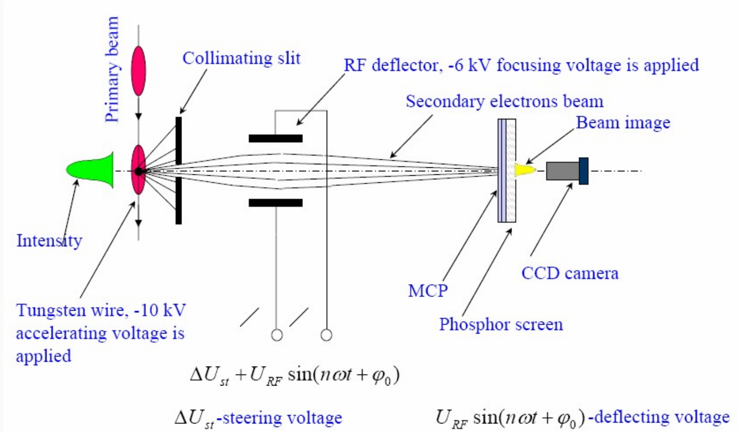
- **momentum and momentum spread** dipole magnet spectrometer (small rigidity Bρ) tran
  - sformation of momentum (spread)
  - into position (spread)
  - spatial resolving detector (screen, SEM,…)



$$\frac{\Delta x}{x_0} = \frac{\Delta p}{p_0}$$

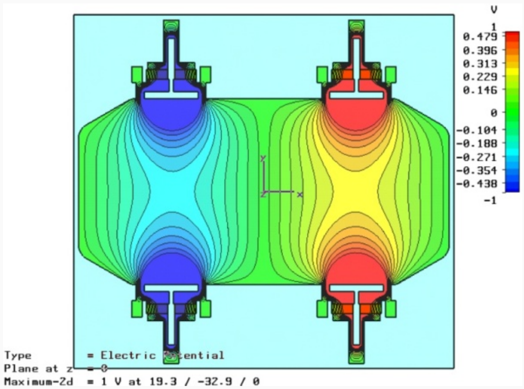
→ alternative method: time of flight (TOF)

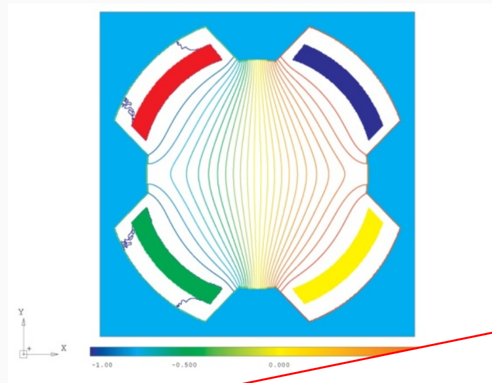
- **bunch shape and time distribution**
  - bunch shape monitor (BSM)
  - primary beam hits thin wire (potential -10 keV) c
  - onversion of primary hadron beam into low energy secondary electrons
  - RF deflector converts time into space coordinates
  - spatial resolving detector

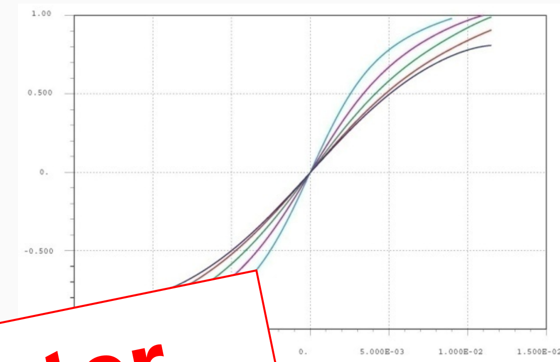


R.Pardo, *RIA Diagnostics Development at Argonne*

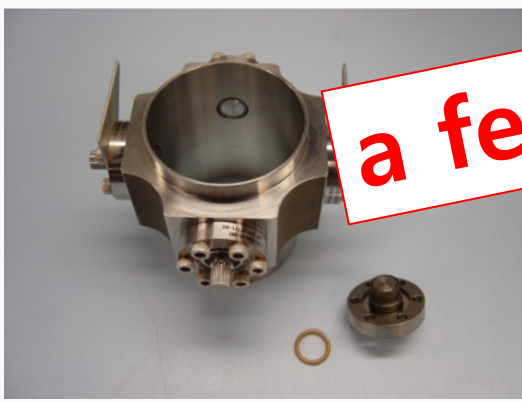
Button & Stripline BPMs

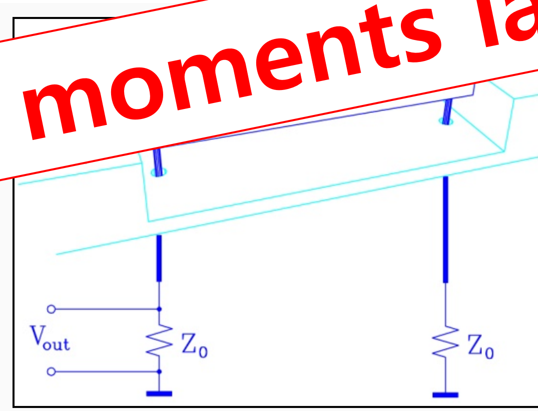


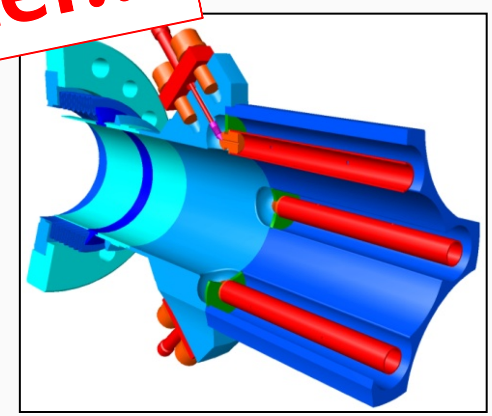


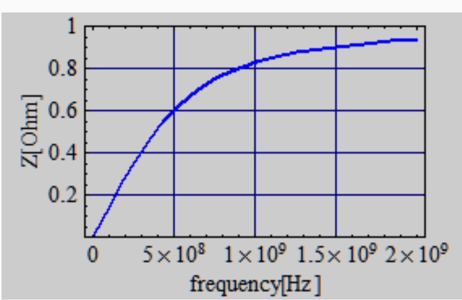


a few moments later...



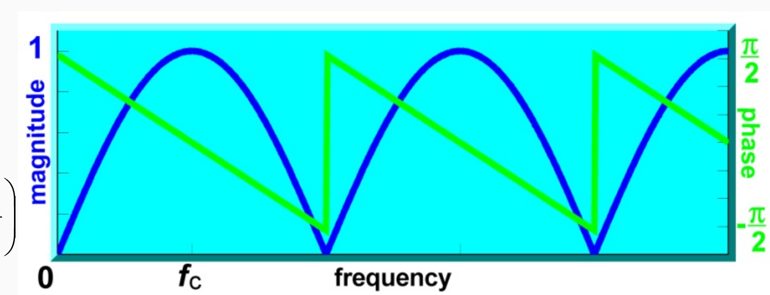






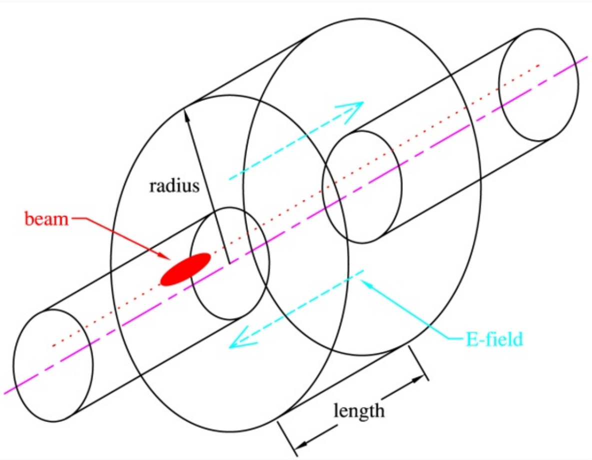
$$Z_{button}(\omega) = Z_0 \frac{r_{button}}{4r_{pipe}} \frac{2r_{button}}{c_0 Z_0 C_{button}} \frac{j\omega Z_0 C_{button}}{1 + j\omega Z_0 C_{button}}$$

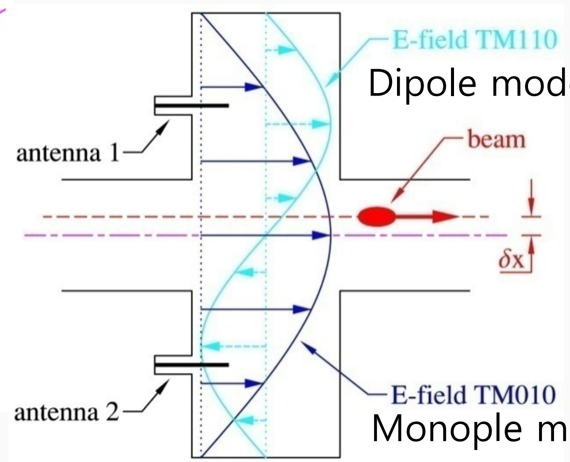
$$Z_{stripline}(\omega) = jZ_0 \exp\left(-j\frac{\omega l}{c_0}\right)\sin\left(\frac{\omega l}{c_0}\right)$$



Introduction / Cavity BPM

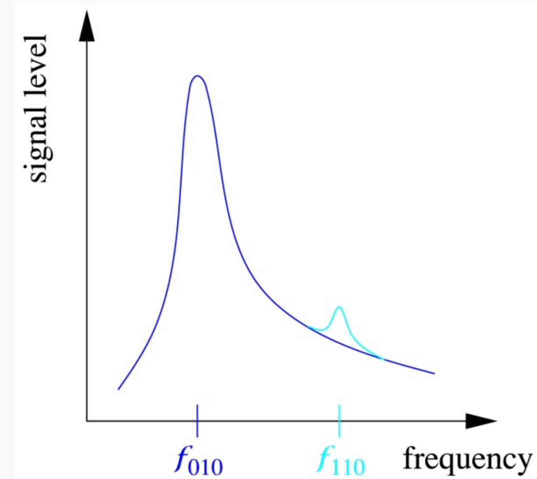
- **Principle** **Generates dipole (TM110) and monopole (TM010) modes**



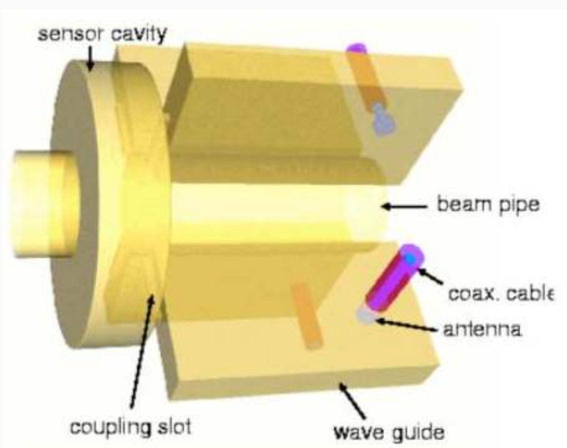


Dipole mode ~ q·δx

Monople mode ~ q



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).**

Resources and References

- Peter Forck: Lecture on Beam Instrumentation and Diagnostics at the Joint University Accelerator School (JUAS),
  - see also the extended Bibliography. http://www-bd.gsi.de/conf/juas/juas.html

- CERN Accelerator Schools (CAS): https://cas.web.cern.ch/previous-schools and http://cas.web.cern.ch/cas/CAS_Proceedings.html

  - Rhodri Jones and Hermann Schmickler: Introduction to Beam Instrumentation and Diagnostics, CERN-2006-002.
  - Daniel Brandt (Ed.), 2008 CAS on Beam Diagnostics for Accelerators, Dourdan, CERN-2009-005 (2009).
  - Heribert Koziol, Beam Diagnostic for Accelerators, Loutraki, Greece (2000), CERN/PS 2001-012 (DR), see also extended Bibliography.
  - Jacques Bosser (Ed.), Beam Instrumentation, CERN-PE-ED 001-92, Rev. 1994
  - Kay Wittenburg (DESY), Beam diagnostic instruments at 3rd and 4th generation light sources, Tuusula, Finland, 2008 CAS.

Summary

- Why do we need beam diagnostics ?
- Beam Parameters and Diagnostics
- Several type of beam diagnostics instrumentation.
- More detailed things about Beam Position Monitor

2022 가속기 및 빔 라인 미래인재 양성 교육단 여름학교

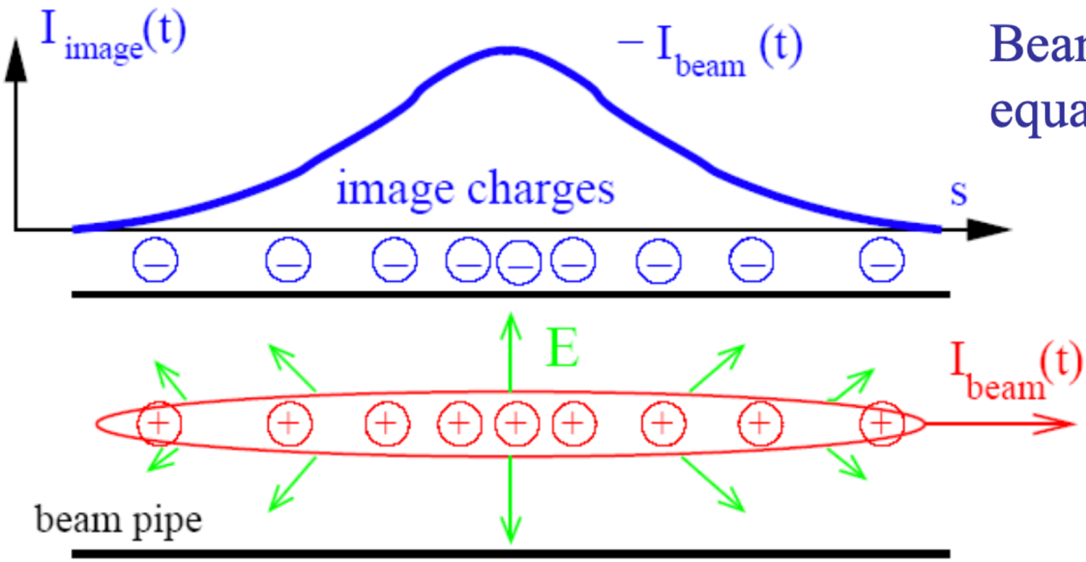
4GSR Beam Diagnostics 2

Korea University
Siwon Jang

01. INTRODUCTION OF BEAM POSITION MONITOR

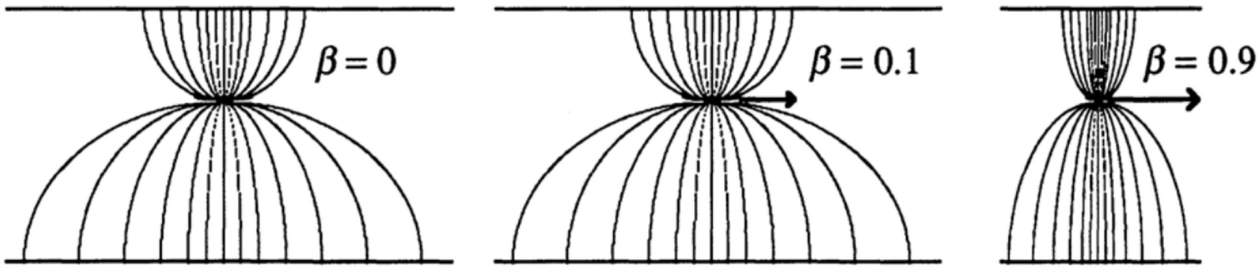
General Idea: Detection of Wall Charges

The image current at the vacuum wall is monitored on a high frequency basis i.e. the ac-part given by the bunched beam.



Beam Position Monitor BPM equals Pick-Up PU

For relativistic velocities, the electric field is mainly transversal: $E_{\perp,lab}(t) = \gamma \cdot E_{\perp,rest}(t)$



Usage of BPMs

A BPM is an non-destructive device

It has a low cut-off frequency i.e. dc-beam behavior can not be monitored
(exception: Schottky spectra, here the physics is due to finite number of particles)

⇒Usage with bunched beams!

It delivers information about:

1. The center of the beam

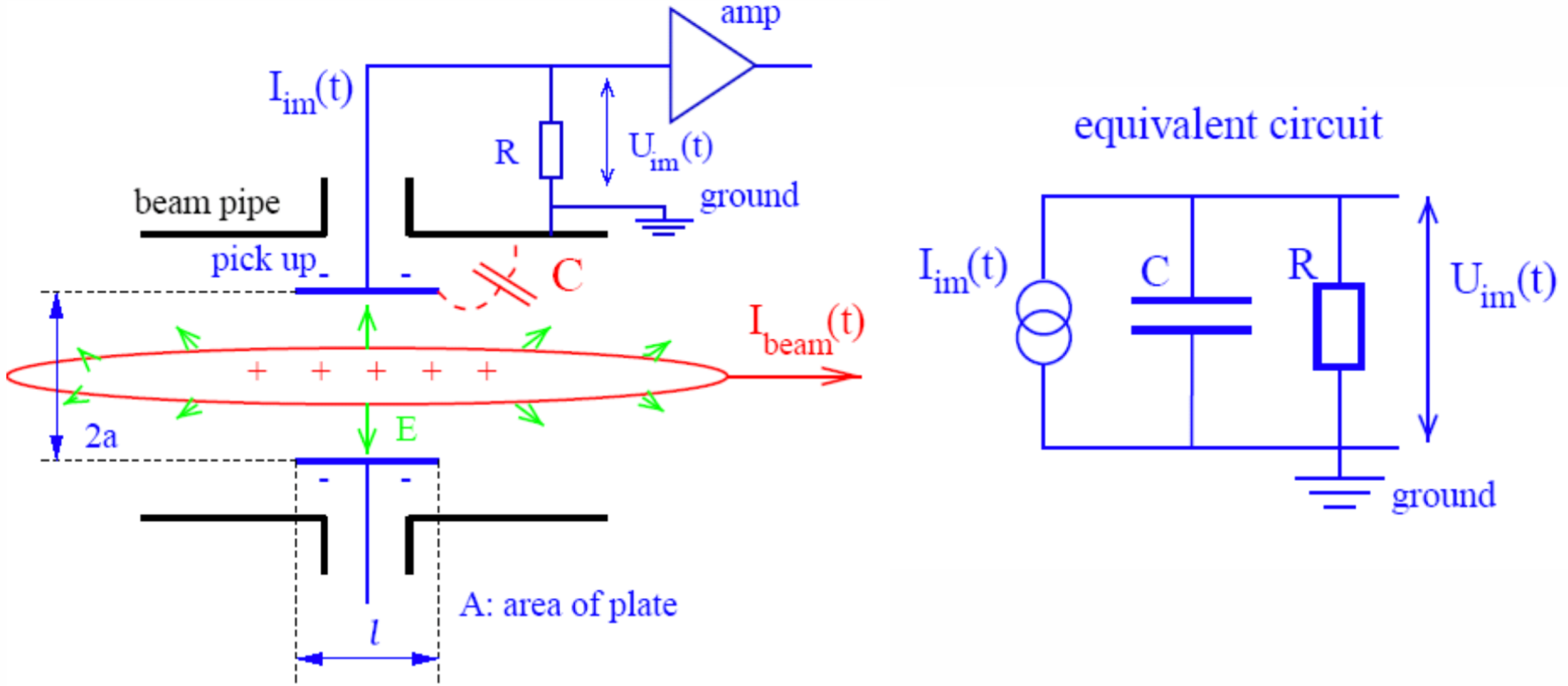
- Closed orbit
  i.e. central orbit averaged over a period much longer than a betatron oscillation
- Bunch position on a large time scale: bunch-by-bunch → turn-by-turn → averaged position
- Single bunch position → determination of parameters like tune, chromaticity, β-function
- Time evolution of a single bunch can be compared to 'macro-particle tracking' calculations
- Feedback: fast bunch-by-bunch damping → precise (and slow) closed orbit correction

2. Longitudinal bunch shapes

- Bunch behavior during storage and acceleration
- For proton LINACs: the beam velocity can be determined by two BPMs
- Low current ***relative*** measurement down to 10 nA.

Model for Signal Treatment of capacitive BPMs

The wall current is monitored by a plate or ring inserted in the beam pipe:



The image current I_{im} at the plate is given by the beam current and geometry:

$I_{im}(t) \equiv dQ_{im}/dt = A/\pi al \cdot dQ_{beam}(t)/dt = A/\pi al \cdot l/\beta c \cdot dI_{beam}/dt = A/\pi a \cdot 1/\beta c \cdot i\omega I_{beam}(\omega)$

Using a relation for Fourier transformation: $I_{beam} = I_0 e^{i\omega t} \Rightarrow dI_{beam}/dt = i\omega I_{beam}$.

Principle of Position Determination with BPM

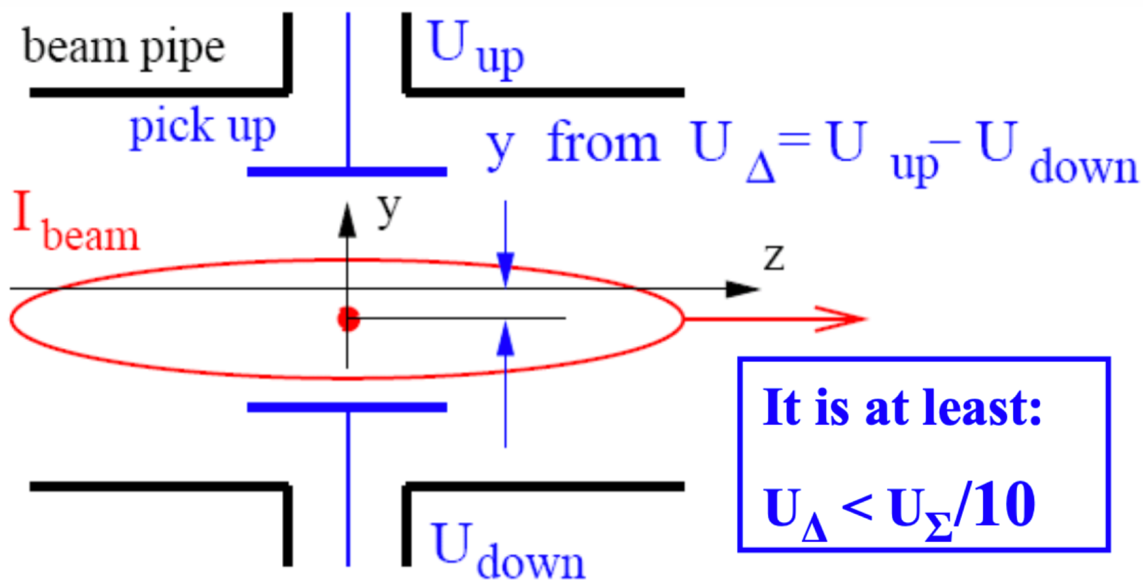
The difference between plates gives the beam's center-of-mass
$\rightarrow$**most frequent application**

'Proximity' effect leads to different voltages at the plates:

$$y = k_y(\omega)\cdot\frac{U_{up}-U_{down}}{U_{up}+U_{down}}+\delta_y(\omega)$$

$$\equiv k_y\cdot\frac{U_\Delta}{U_\Sigma}+\delta_y \equiv k_y\cdot\frac{\Delta}{\Sigma}+\delta_y$$

$$x = k_x(\omega)\cdot\frac{U_{right}-U_{left}}{U_{right}+U_{left}}+\delta_x(\omega)$$



It is at least:
$U_\Delta < U_\Sigma/10$

Sometimes the transverse transfer impedance is defined via $\boldsymbol{U_\Delta = Z_\perp(\omega)\cdot xI_{beam}}$

It can be assumed: $\boldsymbol{Z_\perp(\omega,x)=k(\omega,x)\cdot Z_t(\omega)}$

with $\boldsymbol{k(\omega,x)}$ or $\boldsymbol{S(\omega,x)=1/k(\omega,x)}$ called **displacement sensitivity**

They are geometry dependent, non-linear function, which have to be optimized.

Units: $\boldsymbol{k}$=[mm] and $\boldsymbol{S}$=[%/mm] or $\boldsymbol{S}$=[dB/mm]

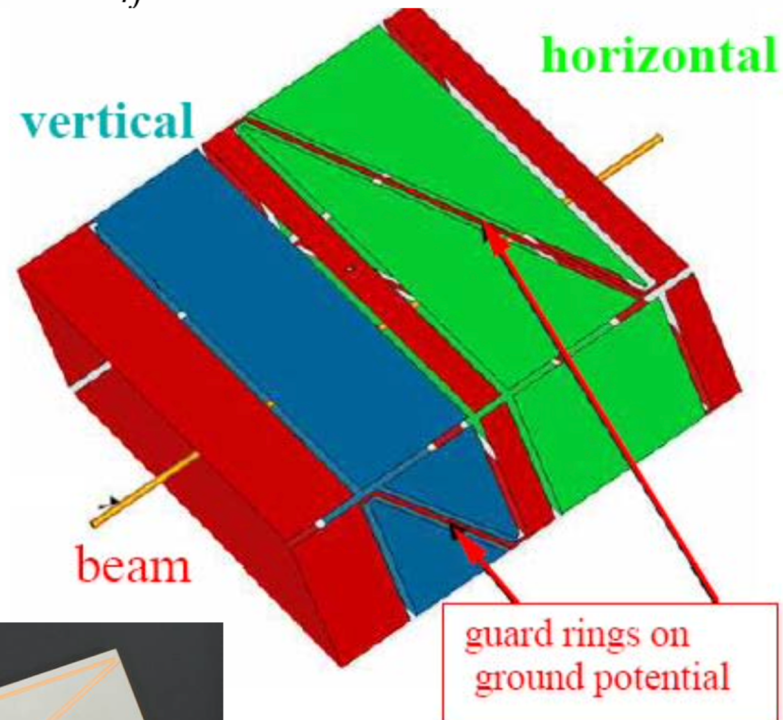
02. TYPE OF BPM

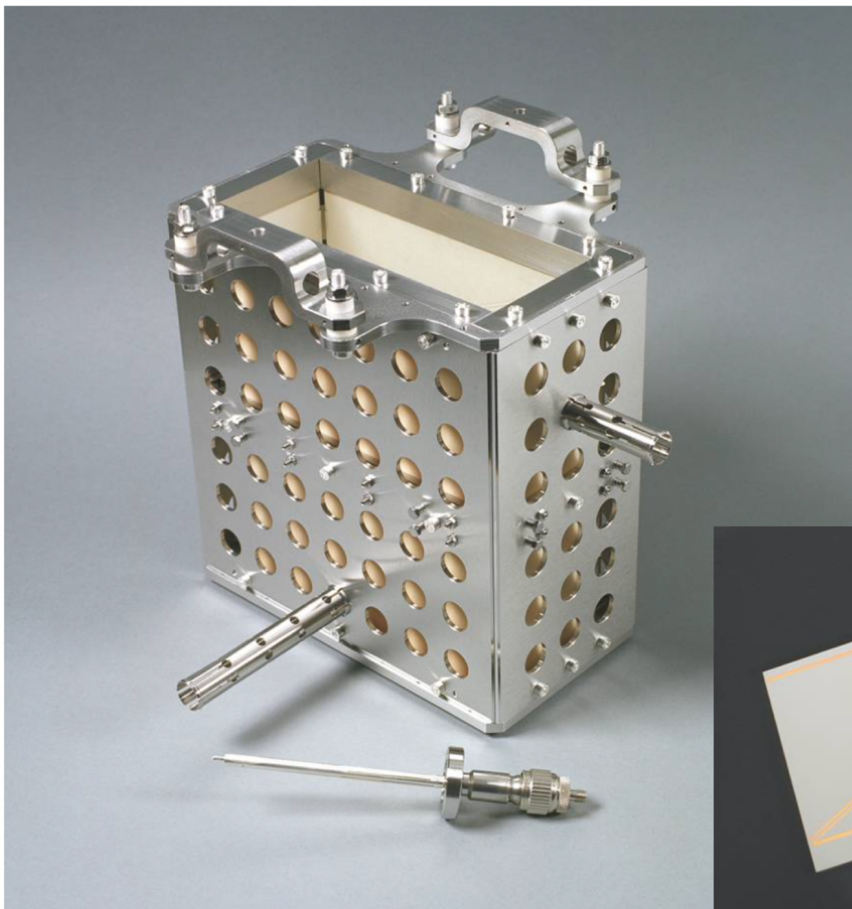
Shoe-box BPMs

Shoe-box BPMs used at low β proton & ion synchrotron for 1MHz < f_{rf} < 10MHz.

Example: HIT cancer therapy synchrotron 0.8 MHz < f_{rf} < 5 MHz

Aperture 180x70 mm^2





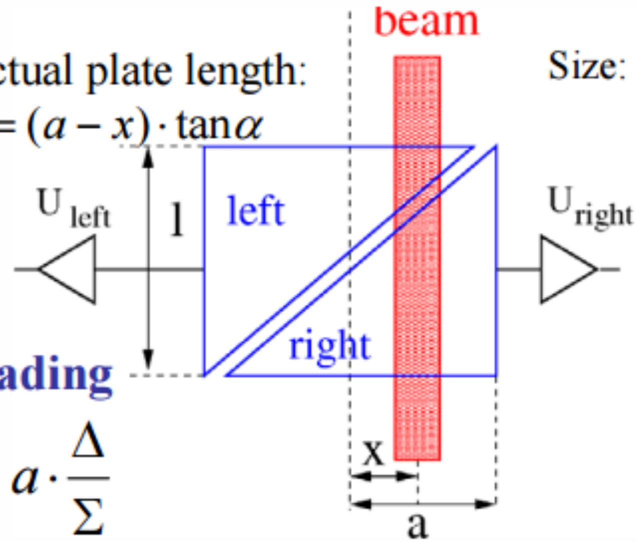
Shoe-box BPM for Proton or Ion Synchrotron

Frequency range: 1 MHz$<f_{rf}<$10 MHz $\Rightarrow$ bunch-length >> BPM length.

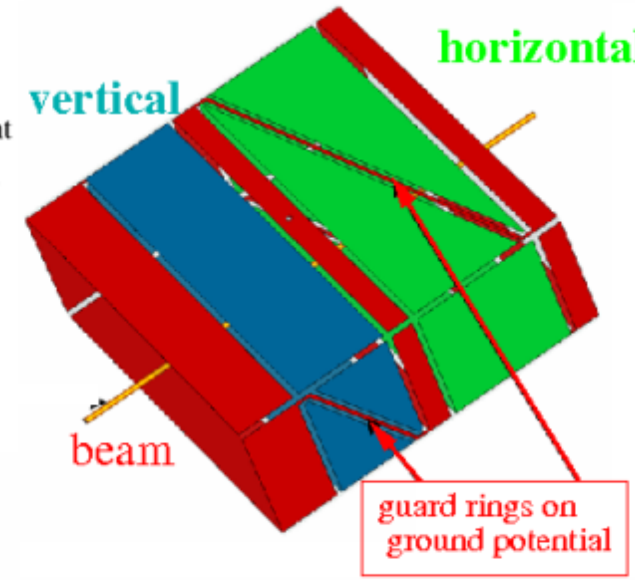
Signal is proportional to actual plate length:

$$l_{right} = (a+x)\cdot\tan\alpha,\; l_{left} = (a-x)\cdot\tan\alpha$$

$$\Rightarrow \frac{l_{right} - l_{left}}{l_{right} + l_{left}} = \frac{x}{a}$$

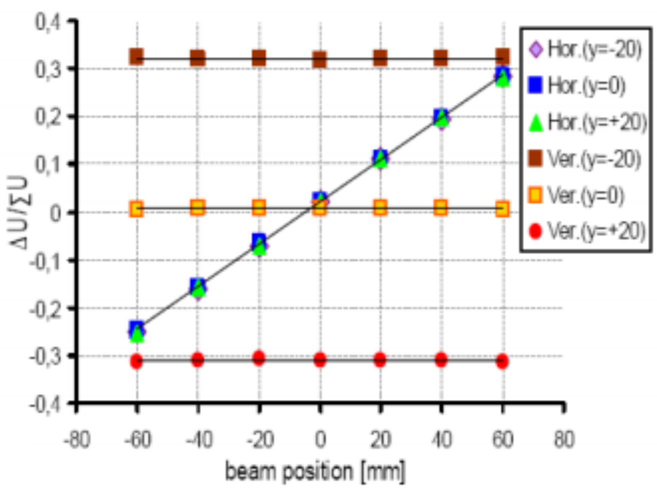


Size: 200x70 mm^2



In ideal case: linear reading

$$x = a\cdot\frac{U_{right} - U_{left}}{U_{right} + U_{left}} \equiv a\cdot\frac{\Delta}{\Sigma}$$



Shoe-box BPM:

Advantage: Very linear, low frequency dependence

Disadvantage: Large size, complex mechanics
high capacitance

Button BPM for short Bunches

LINACs, e⁻-synchrotrons: 100 MHz < f_{rf} < 3 GHz → bunch length ≈ BPM length

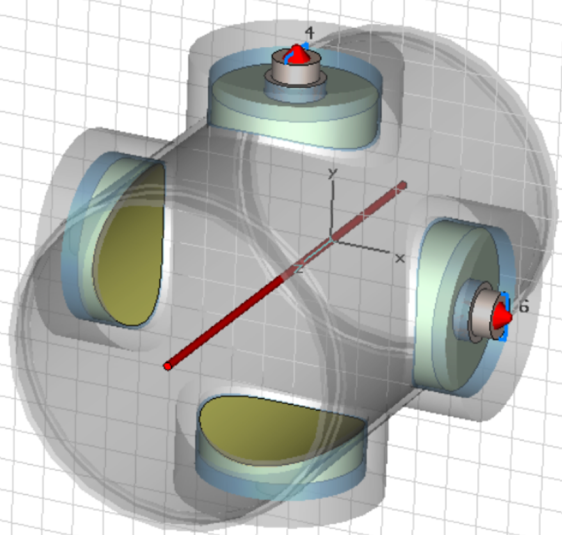
→ 50 Ω signal path to prevent reflections

Button BPM with 50 Ω ⇒ $U_{im}(t) = R \cdot \frac{A}{\beta c \cdot \pi a} \cdot \frac{dI_{bea}}{dt}$

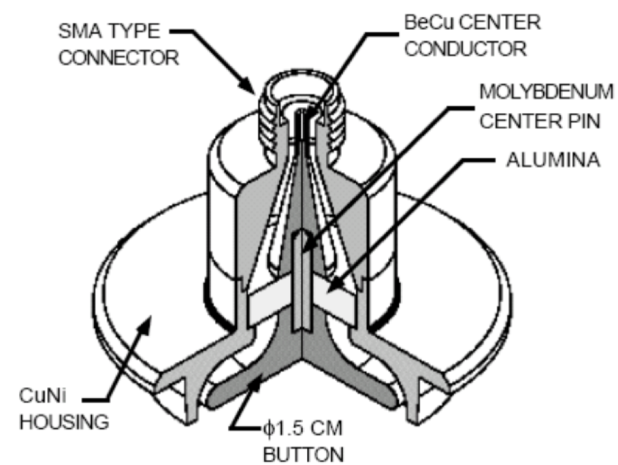
Example: LHC-type inside cryostat:

∅24 mm, half aperture a=25 mm, C=8 pF

⇒ f_{cut}=400 MHz, Z_∞ = 1.3 Ω:



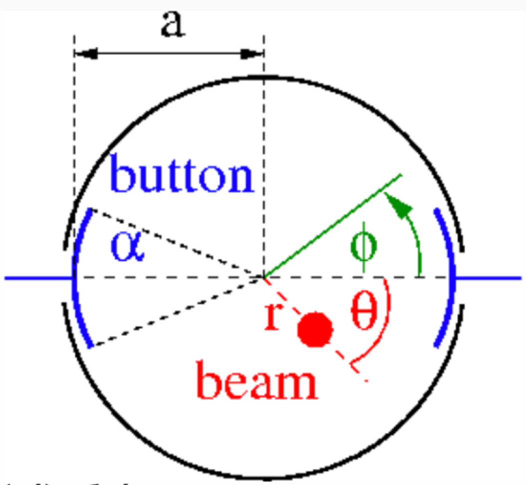
From C. Boccard (CERN)



Button BPM for short Bunches

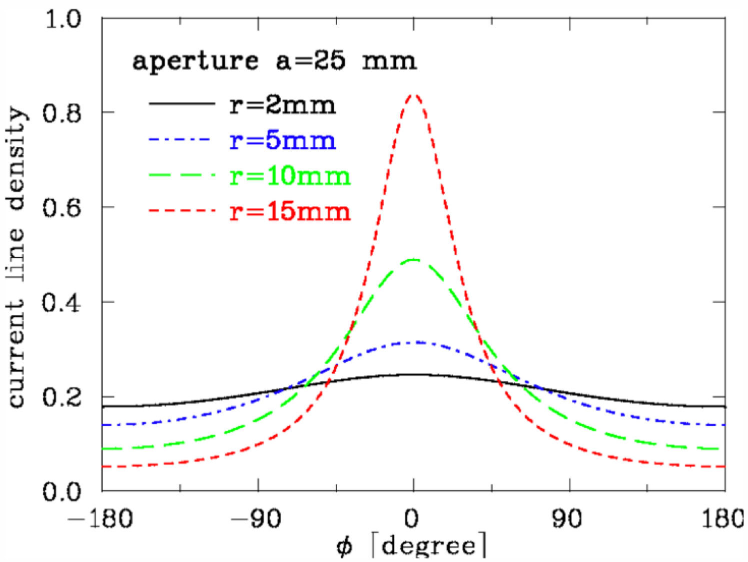
'Proximity effect': larger signal for closer plate

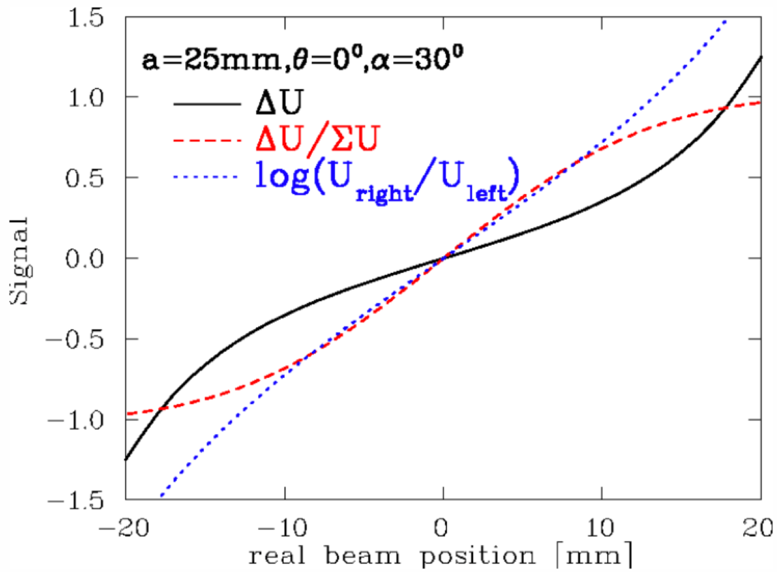
<u>**Ideal 2-dim case:**</u> Cylindrical pipe → image current density via 'image charge method' for 'pensile' beam:



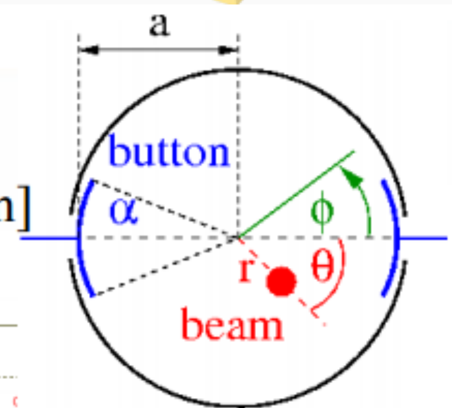
$$j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left(\frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right)$$

Image current: Integration of finite BPM size: $I_{im} = \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi) d\phi$





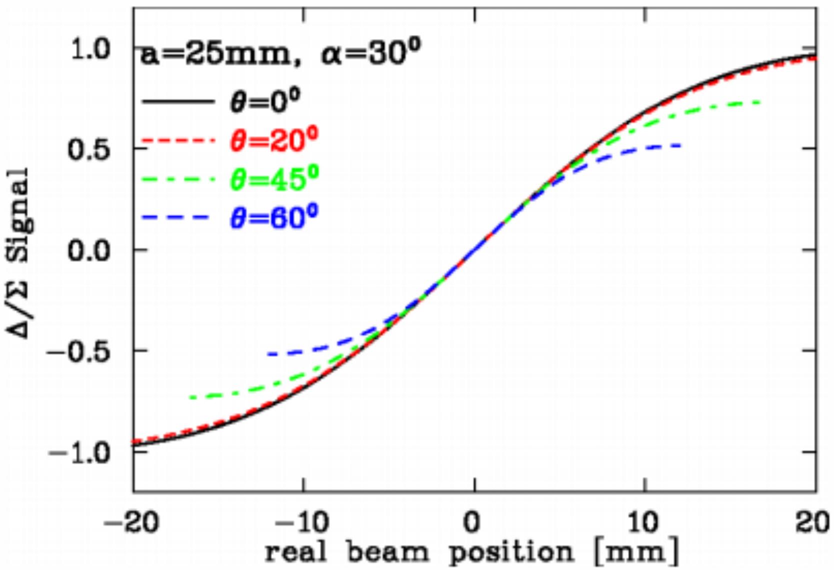
Button BPM for short Bunches

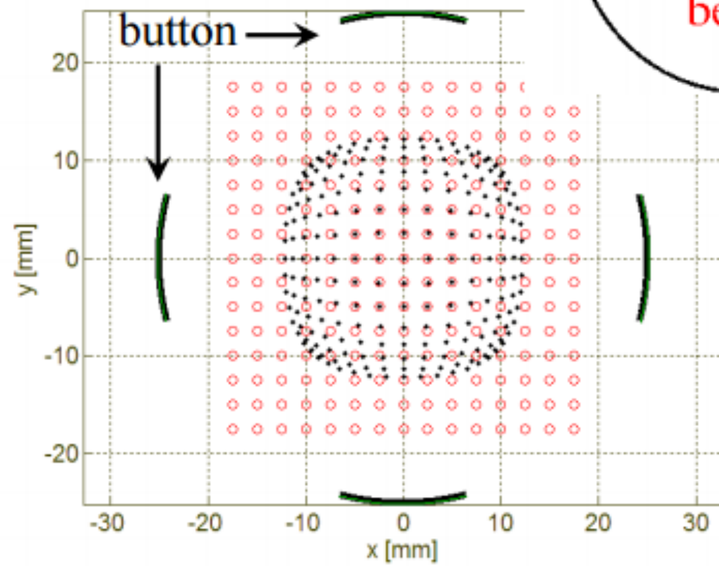


Ideal 2-dim model: Non-linear behavior and hor-vert coupling:

Sensitivity: $x=k\cdot\Delta/\Sigma = 1/S\cdot\Delta/\Sigma$ with k [mm], S [%/mm] or [dB/mm]

For this example: center part S=7.4%/mm ⇔ $k=1/S$=14mm





Current density can also be calculated by Laplace equation for Fourier components

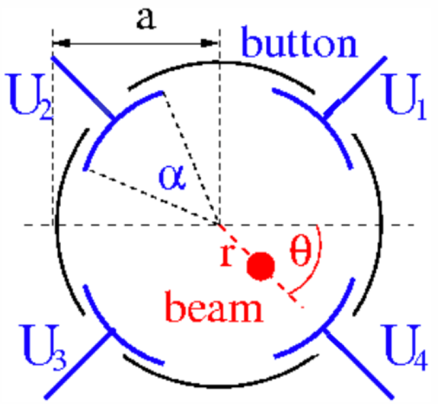
$$I_{beam} = \langle I_{beam} \rangle + 2\langle I_{beam} \rangle \cdot \sum_{n=1}^{\infty} A_n \cos(n\omega_0 t) \quad \text{for Gaussian bunches}: A_n = \exp(-n^2\omega^2\sigma_t^2/2)$$

In addition, frequency dependence can be calculated by this method.

Button BPM at Synchrotron Light Sources

The button BPM can be rotated by 45^0
to avoid exposure by synchrotron light:

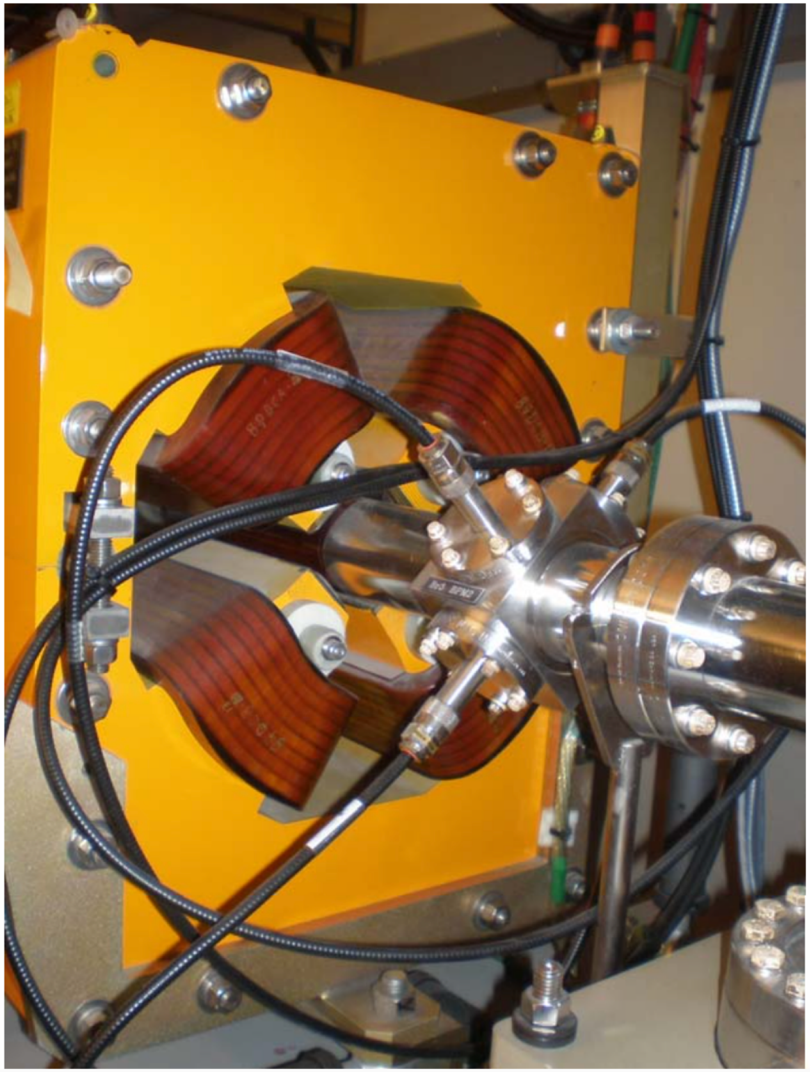
Frequently used at boosters for light sources



$$\text{horizontal}: x = \frac{1}{S} \cdot \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

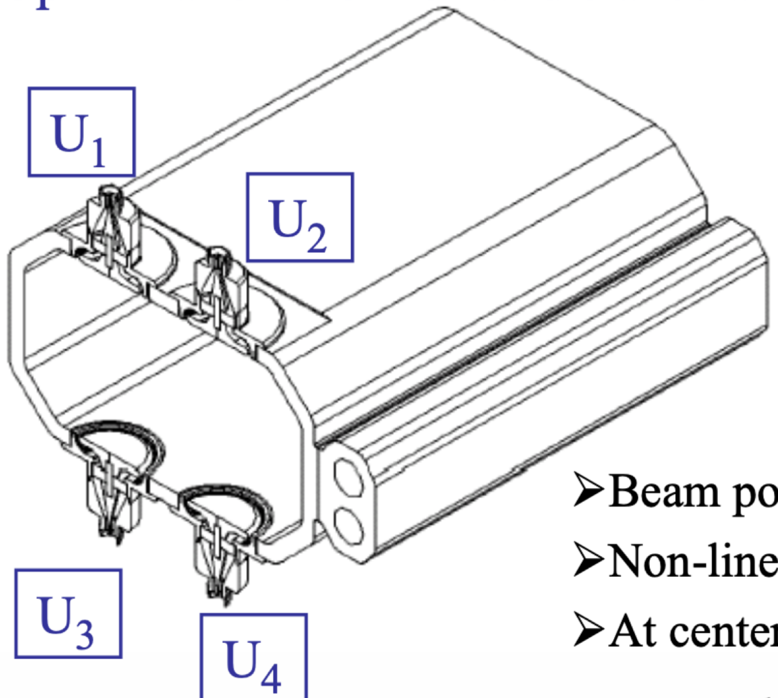
$$\text{vertical}: \quad y = \frac{1}{S} \cdot \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4}$$

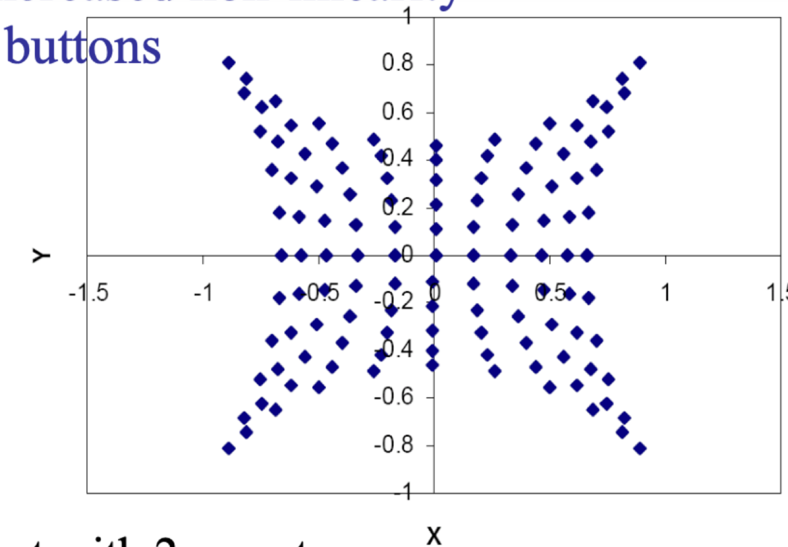
Example: Booster of ALS, Berkeley



Button BPM at Synchrotron Light Sources

Due to synchrotron radiation, the button insulation might be destroyed
⇒buttons only in vertical plane possible ⇒ increased non-linearity
Optimization: horizontal distance and size of buttons





- Beam position swept with 2 mm steps
- Non-linear and inter-plane dependent sensitivity
- At center S_x=8.5%/mm in this case

$$\text{horizontal}: x = \frac{1}{S_x} \cdot \frac{(U_2 + U_4) - (U_1 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

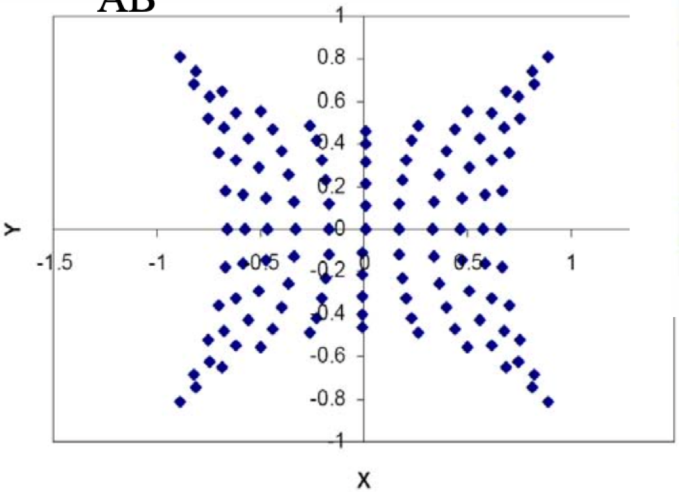
$$\text{vertical}: y = \frac{1}{S_y} \cdot \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4}$$

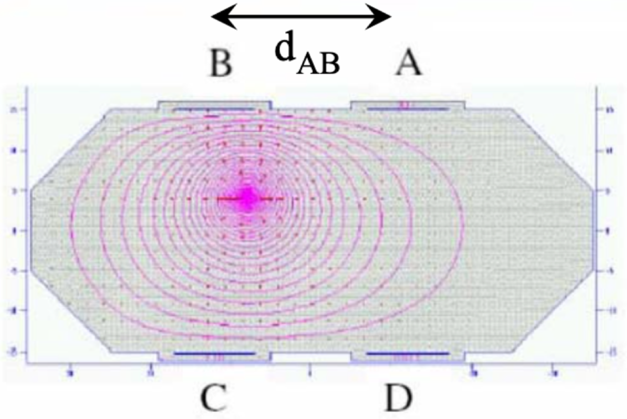
From S. Varnasseri, SESAME, DIPAC 2005

Button BPM at Synchrotron Light Sources

2-dim electro-static simulation:

d_{AB}=24 mm

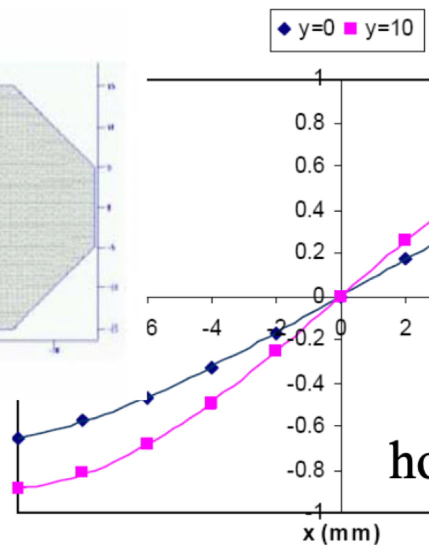




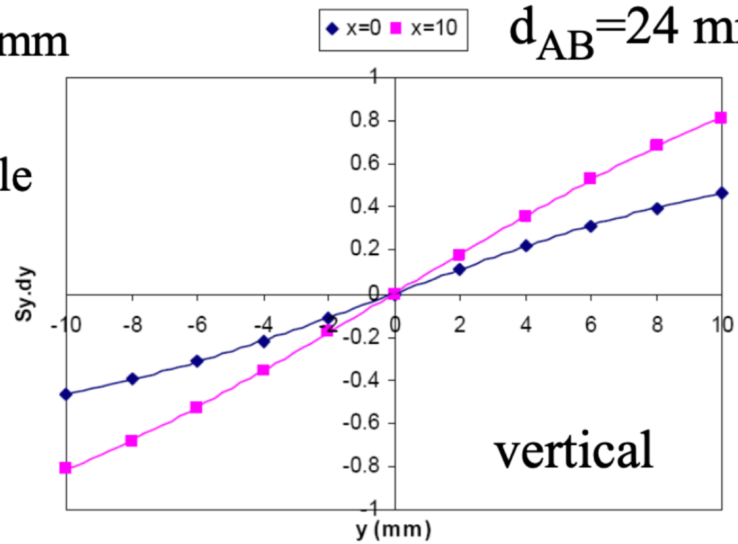
Result:

- Hori. S_x=8.5%/mm
- Vertical S_y=5.6%/mm
- x&y dependent polynomial fit possible

d_{AB}=24 mm



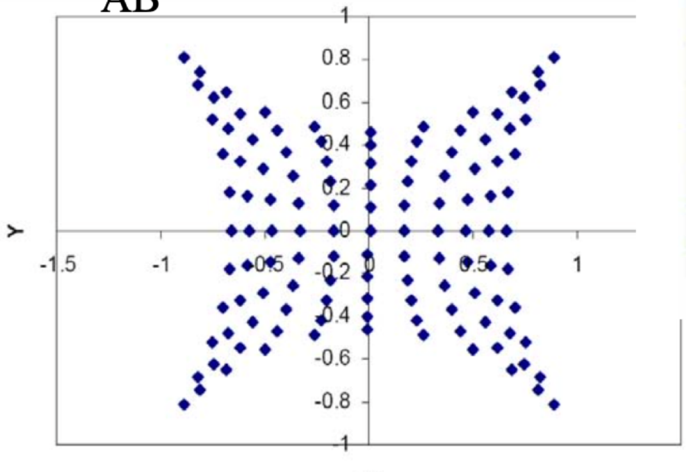
d_{AB}=24 mm



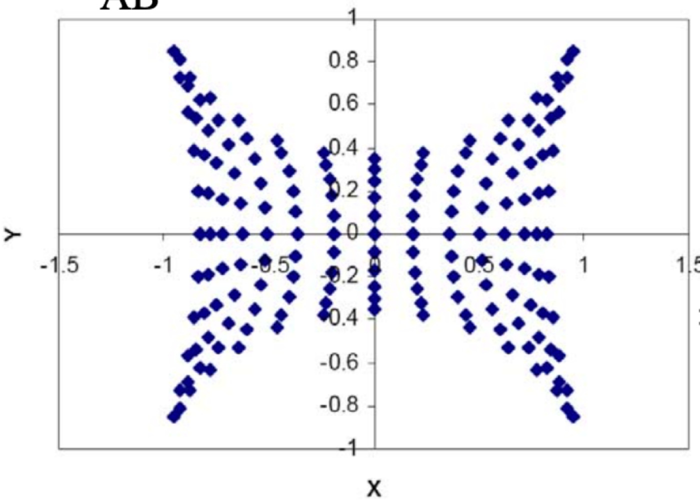
Button BPM at Synchrotron Light Sources

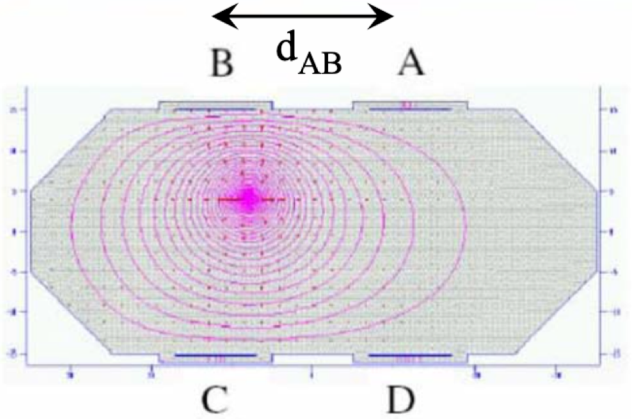
2-dim electro-static simulation:

d_{AB}=24 mm



d_{AB}=30 mm





Result:

Distance d_{AB} influences the sensitivity

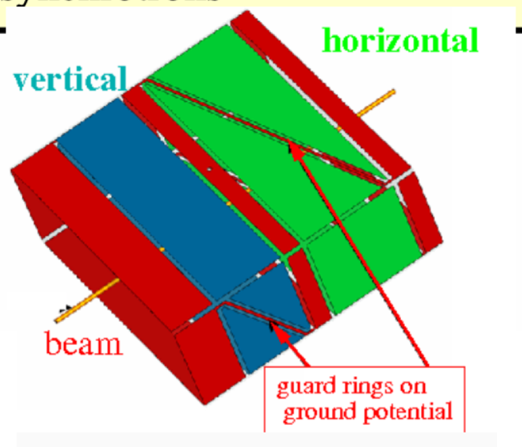
Larger d_{AB} has the effect:

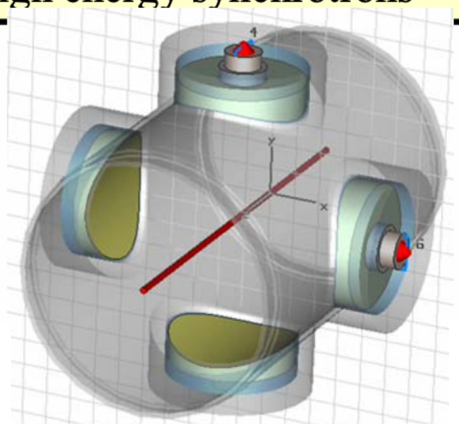
- higher sensitivity in x-direction
- lower sensitivity in y-direction
- linearity in influenced

⇒ Numerical optimization required

Comparison Shoe-Box and Button BPM

	Shoe-Box BPM	Button BPM
Precaution	Bunches longer than BPM	Bunch length comparable to BPM
Shape	Rectangular, cut cylinder	Orthogonal or in-plane orientation
BPM length (typical)	10 to 20 cm length per plane	∅1 to 3 cm per button
Bandwidth (typical)	0.1 to 100 MHz	100 MHz to 5 GHz
Coupling	1 MΩ or ≈1 kΩ (transformer)	50 Ω
Cutoff frequency (typical)	0.01… 10 MHz (*C*=30…100pF)	0.3… 1 GHz (*C*=2…10pF)
Linearity	Very good, no x-y coupling	Non-linear, x-y coupling
Sensitivity	Good, care: plate cross talk	Good, care signal matching
Usage	At (low energy) proton synchrotrons	All electron acc., proton Linacs, high energy synchrotrons





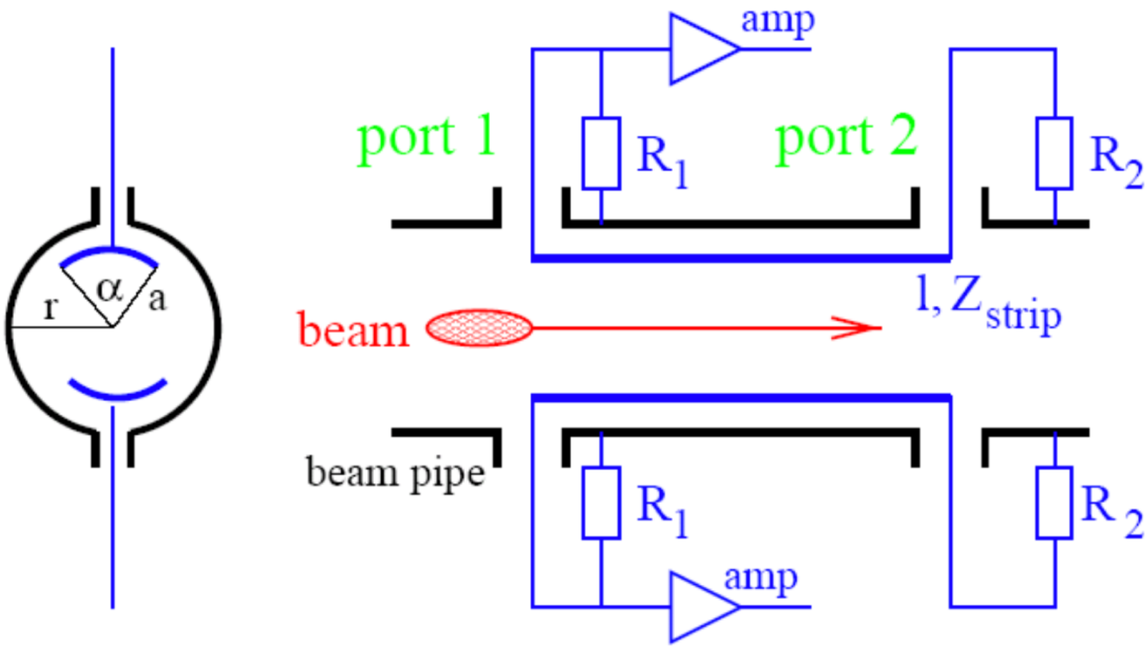
Stripline BPM: General Idea

For short bunches, the ***capacitive*** button deforms the signal

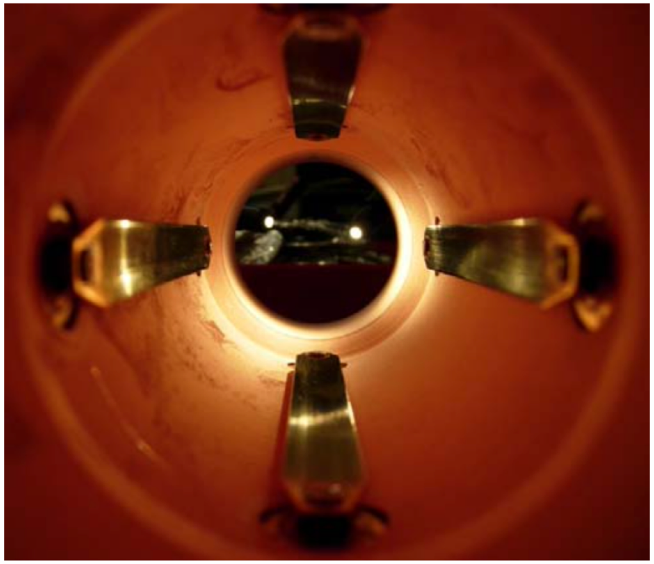
→ Relativistic beam $\beta \approx 1 \Rightarrow$ field of bunches nearly TEM wave

→ Bunch's electro-magnetic field induces a **traveling pulse** at the strips

→ Assumption: Bunch shorter than BPM, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$.



LHC stripline BPM, l=12 cm



From C. Boccard, CERN

Stripline BPM: General Idea

For relativistic beam with $\beta \approx 1$ and short bunches:

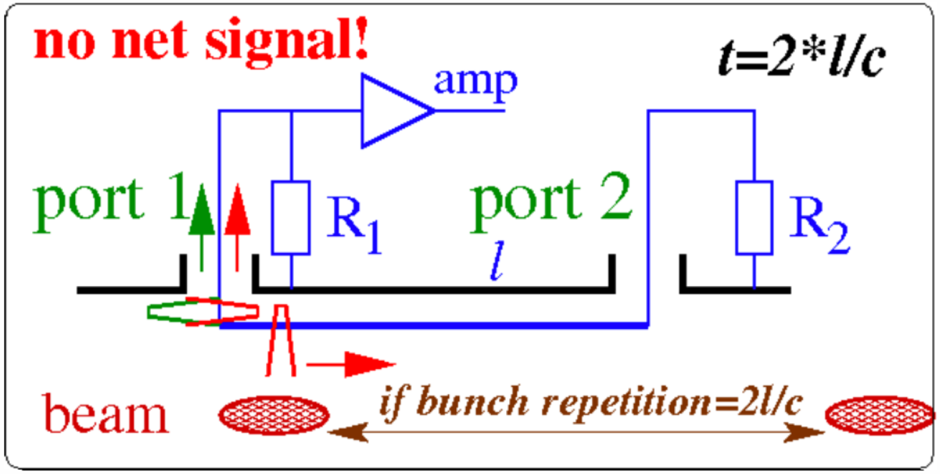
→ Bunch's Electro-magnetic field induces a **traveling pulse** at the strip

→ ***Assumption:*** $l_{bunch} << l$, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$

Signal treatment at upstream port 1:

t=0: Beam induced charges at **port 1**:
→ half to R_1, half toward **port 2**

t=l/c: Beam induced charges at **port 2**:
→ half to R_2, ***but*** due to different sign, it cancels with the signal from **port 1**
→ half signal reflected



t=2·l/c: reflected signal reaches **port 1**

$$\Rightarrow U_1(t) = \frac{1}{2} \cdot \frac{\alpha}{2\pi} \cdot Z_{strip} \left(I_{beam}(t) - I_{beam}(t - 2l/c) \right)$$

If beam repetition time equals 2·l/c: reflected preceding port 2 signal cancels the new one:
→ no net signal at **port 1**

Signal at downstream port 2: Beam induced charges cancels with traveling charge from port 1

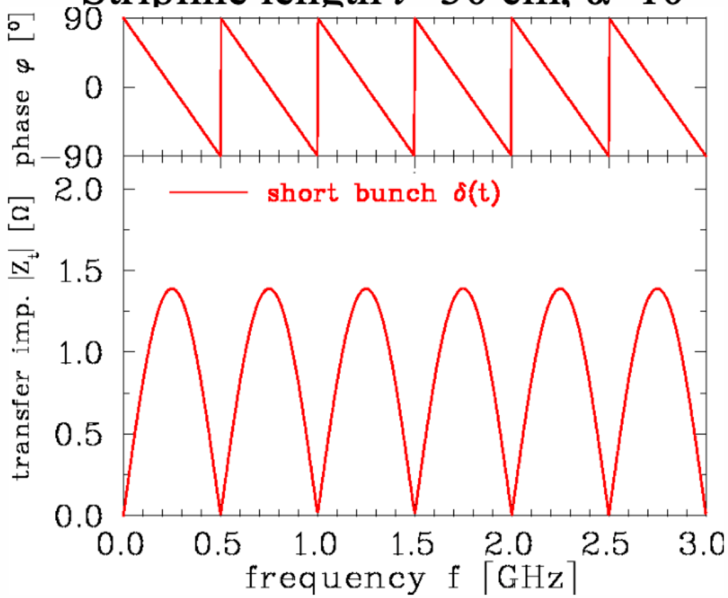
⇒ Signal depends direction ⇔ directional coupler: e.g. can distinguish between e^- and e^+ in collider

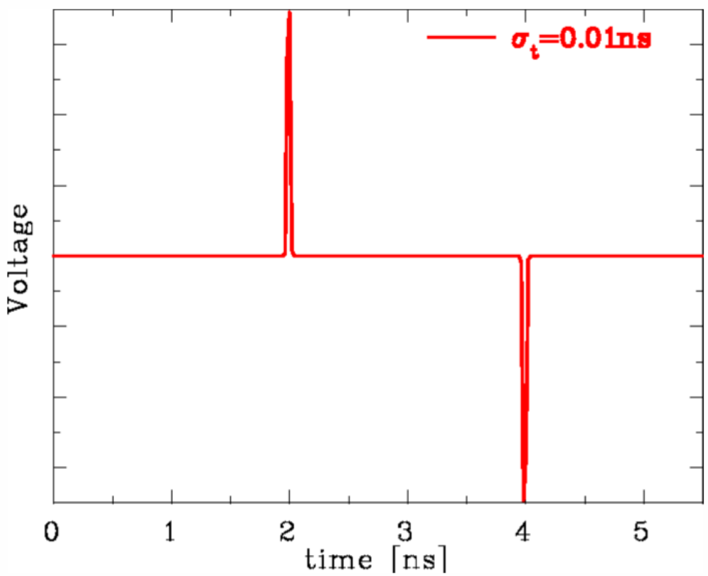
Stripline BPM: Transfer Impedance

The signal from port 1 and the reflection from port 2 can cancel $\Rightarrow$ minima in Z_t

For short bunches $I_{beam}(t) \rightarrow Ne \cdot \delta(t)$: $Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \sin(\omega l / c) \cdot e^{i(\pi/2 - \omega l / c)}$

Stripline length l=30 cm, $\alpha=10^0$





- Z_t show maximum at $l=c/4f=\lambda/4$ i.e. 'quarter wave coupler' for bunch train
  $\Rightarrow$ l has to be matched to v_{beam}
- No signal for $l=c/2f=\lambda/2$ i.e. destructive interference with **subsequent** bunch
- Around maximum of $|Z_t|$: phase shift $\varphi=0$ i.e. direct image of bunch
- $f_{center}=1/4 \cdot c/l \cdot (2n-1)$. For first lope: $f_{low}=1/2 \cdot f_{center}$, $f_{high}=3/2 \cdot f_{center}$ i.e. bandwidth $\approx 1/2 \cdot f_{center}$
- Precise matching at feed-through required t o preserve 50 Ω matching.

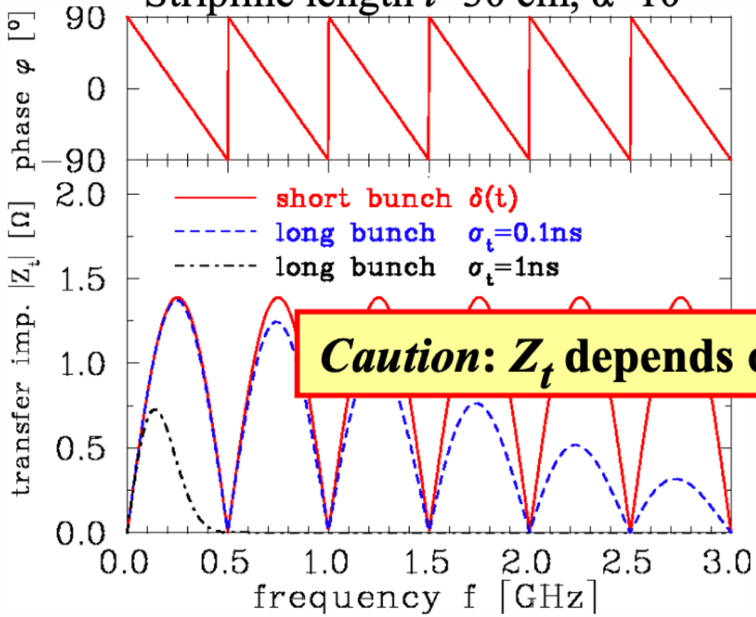
Stripline BPM: Finite Bunch Length

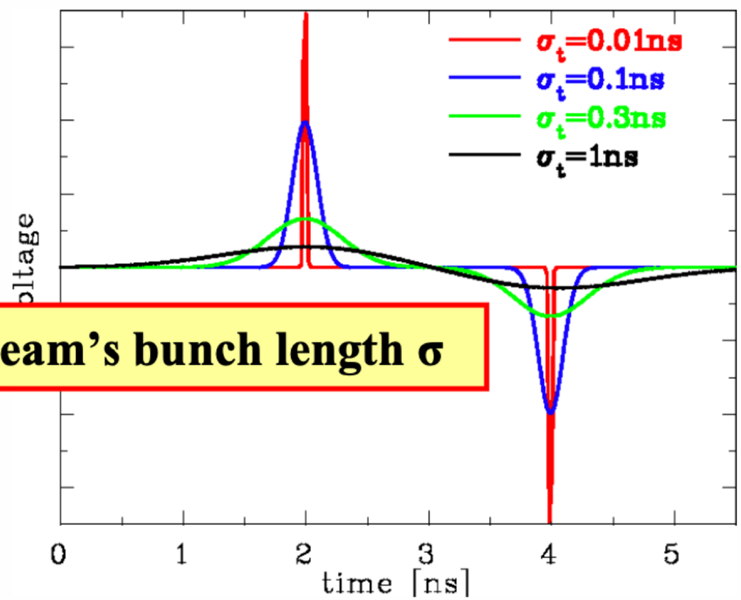
The signal at port 1 for a finite bunch of length σ: $I_{beam}(t) = I_0 \cdot e^{-t^2/2\sigma^2}$

$$\Rightarrow Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot e^{-\omega^2\sigma^2/2} \cdot \sin(\omega l/c) \cdot e^{i(\pi/2 - \omega l/c)}$$

$$\Rightarrow \text{in time domain}: U_{im}(t) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \left(e^{-(t+l/c)^2/2\sigma^2} - e^{-(t-l/c)^2/2\sigma^2}\right) \cdot I_0$$

Stripline length l=30 cm, α=10^0





***Caution*: Z_t depends on beam's bunch length σ**

- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long $(\pm 3\sigma_t > l)$ destructive interference leads to signal damping

  Cure: length of stripline has to be matched to bunch length

2-dim Model for Stripline BPM

'Proximity effect': larger signal for closer plate

2-dim case: Cylindrical pipe → image current density:

$$j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left(\frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right)$$

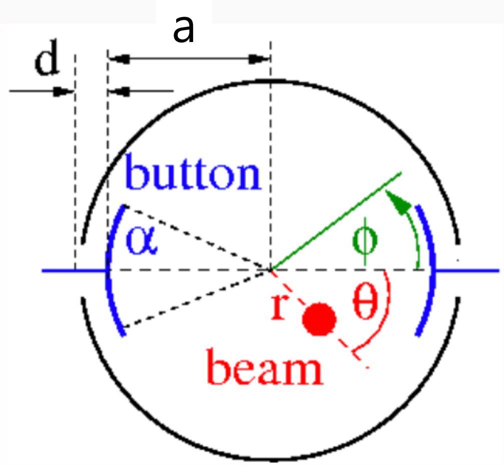
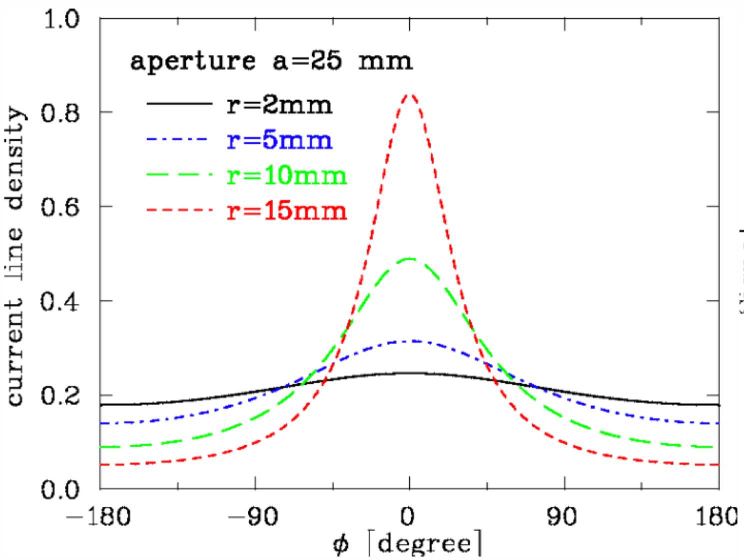
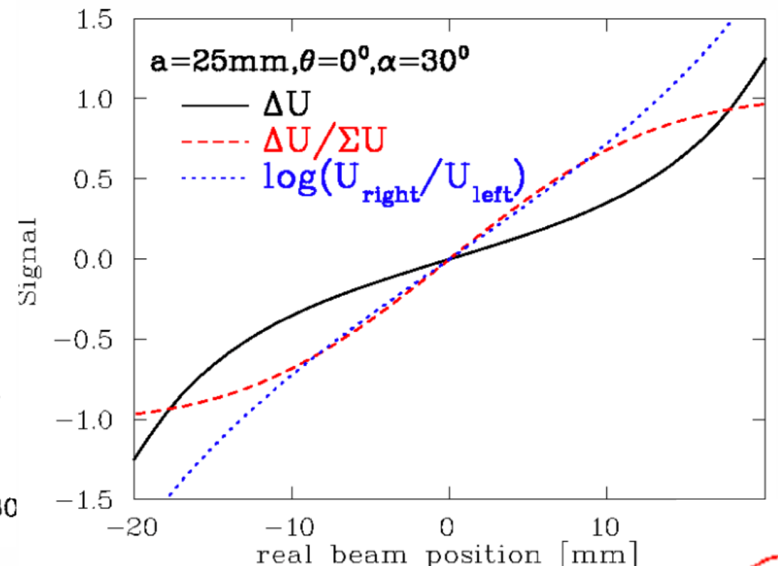


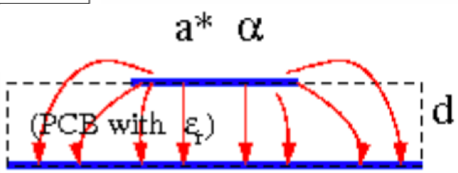
Image current of finite BPM size: $I_{im} = \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi) d\phi$





Impedance Z_{strip}=50Ω:

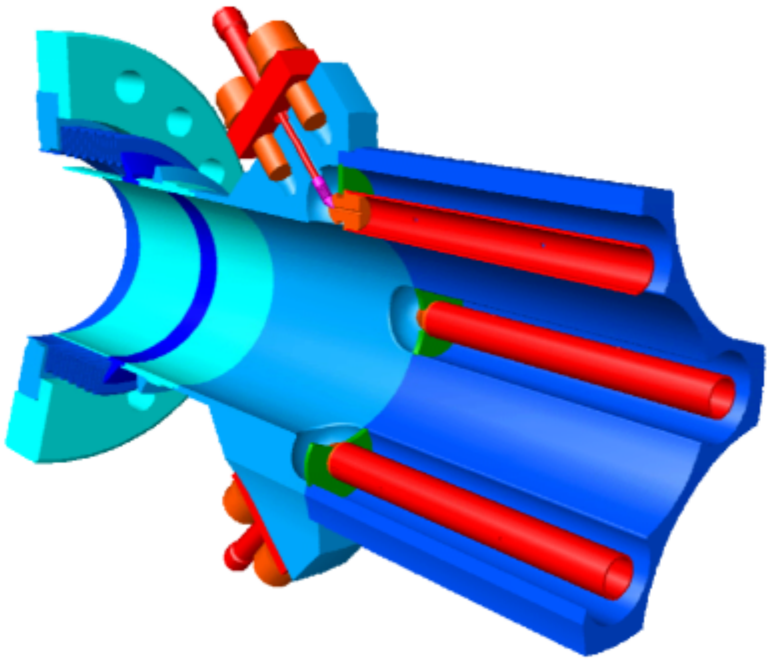
Comparable formula as for PCB micro-strip →dependence on d and α

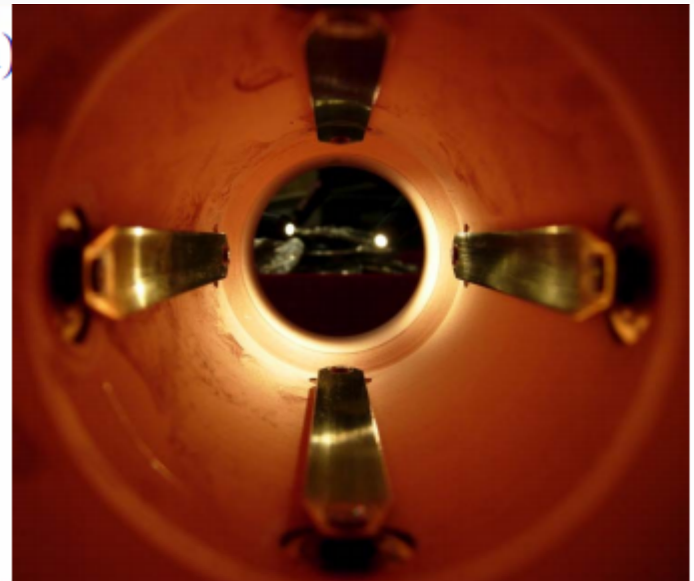


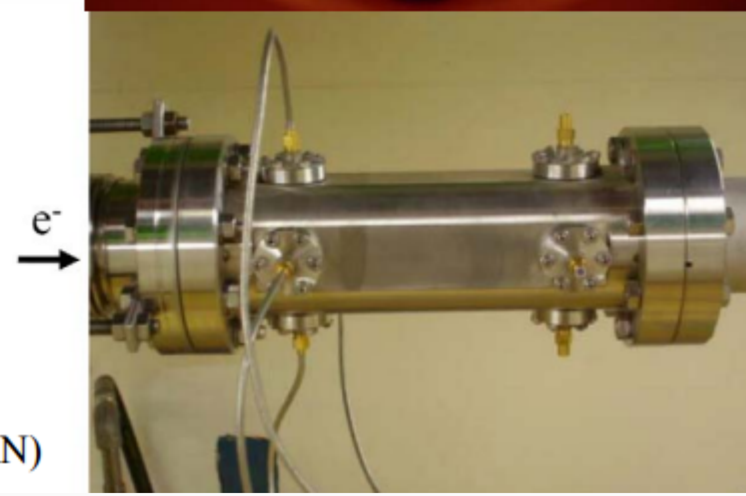
A fabricated Stripline BPM

20 cm stripline BPM at TTF2 (chamber ∅34mm)

And 12 cm LHC type:





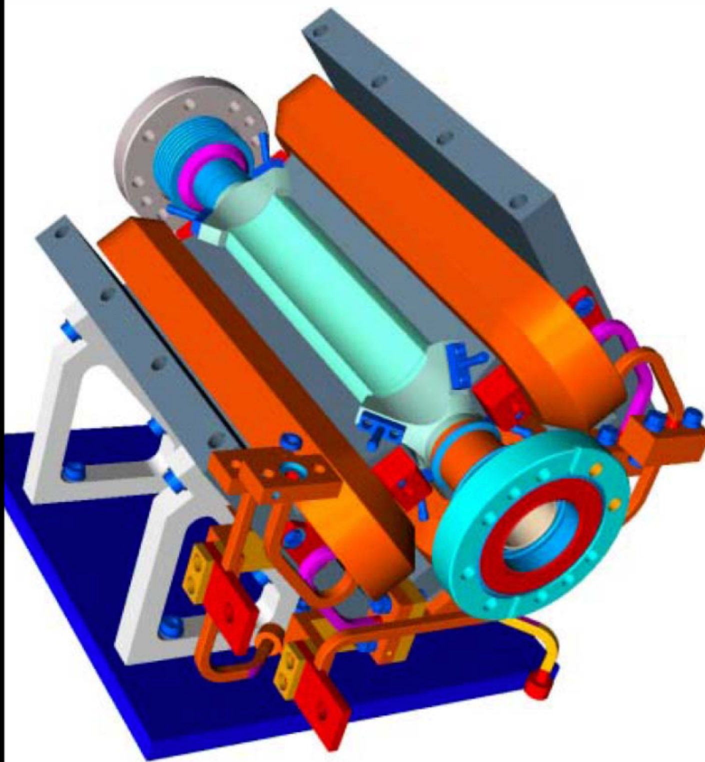


From . S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)

Comparison: Stripline and Button BPM (simplified)

	Stripline	Button
Idea	traveling wave	electro-static
Requirement	Careful Z_{strip}=50Ω matching	
Signal quality	Less deformation of bunch signal	Deformation by finite size and capacitance
Bandwidth	Broadband, but minima	Highpass, but f_{cut}<1 GHz
Signal strength	Large Large longitudinal and transverse coverage possible	Small Size <Ø3cm, to prevent signal deformation
Mechanics	Complex	Simple
Installation	Inside quadrupole possible ⇒improving accuracy	Compact insertion
Directivity	**YES**	No

TTF2 BPM inside quadrupole

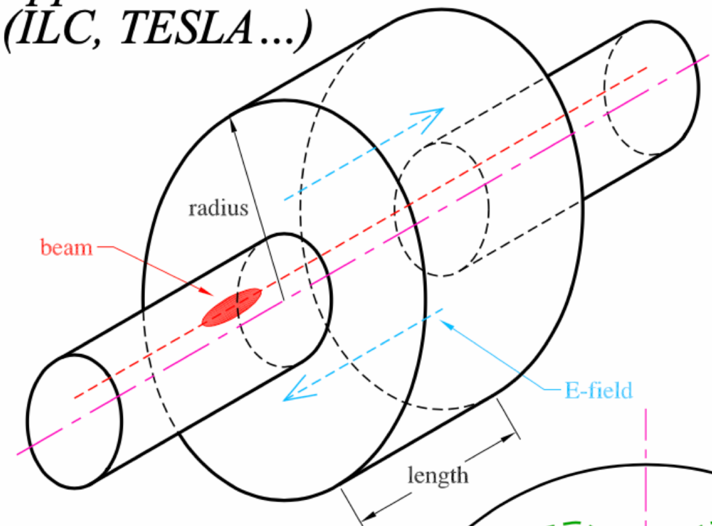


From . S. Wilkins,
D. Nölle (DESY)

Cavity BPM

High resolution on μs time scale can be achieved by excitation of a dipole mode:

Application: small e⁻ beams (ILC, TESLA…)

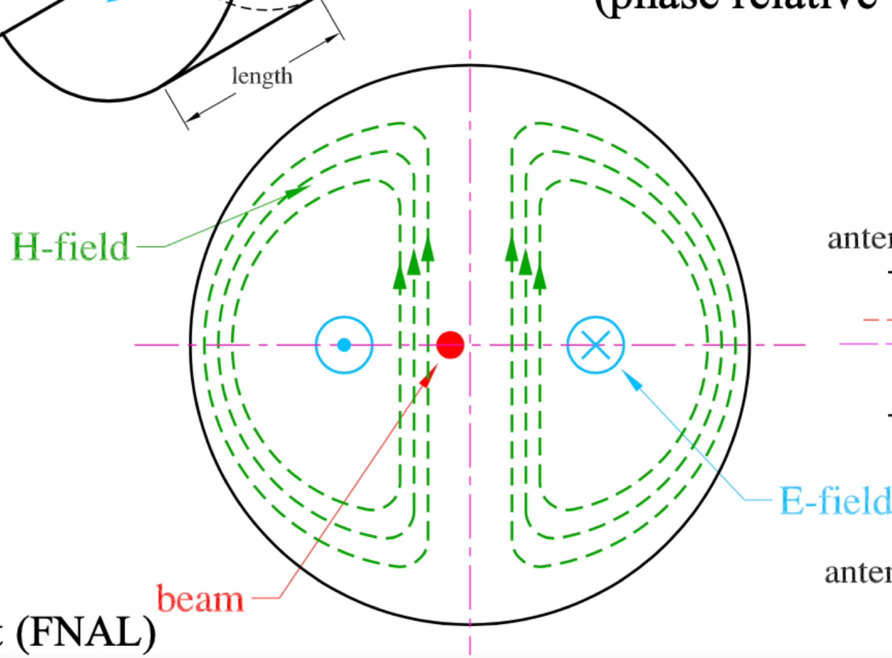


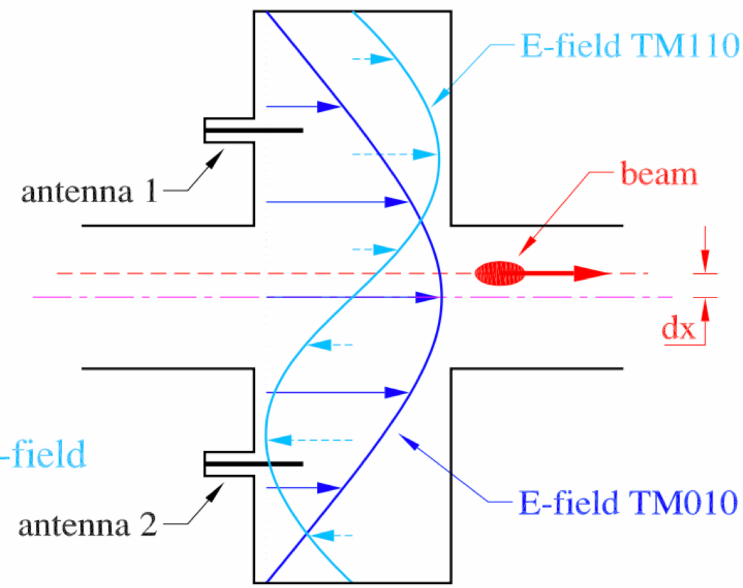
For pill box the resonator modes given by geometry:

- monopole TM_{010} with f_{010}
  → maximum at beam center ⇒ strong excitation
- Dipole mode TM_{011} with f_{011}
  → minimum at center ⇒ excitation by beam offset

⇒ Detection of dipole mode amplitude

(phase relative to monopole gives sign of displacement)



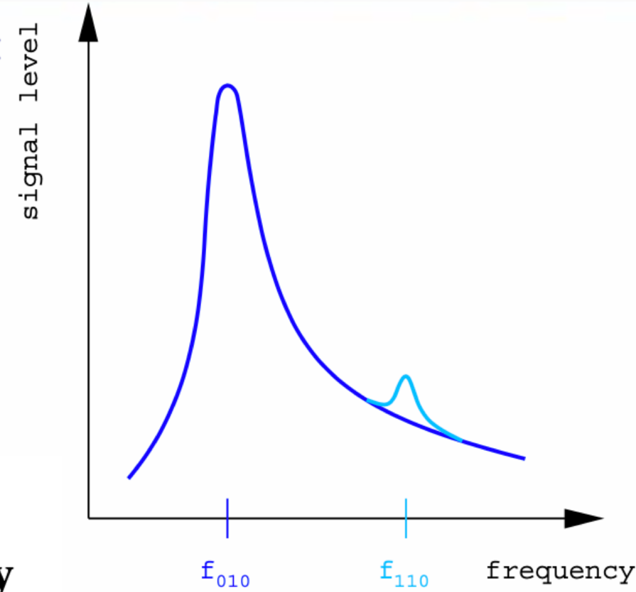


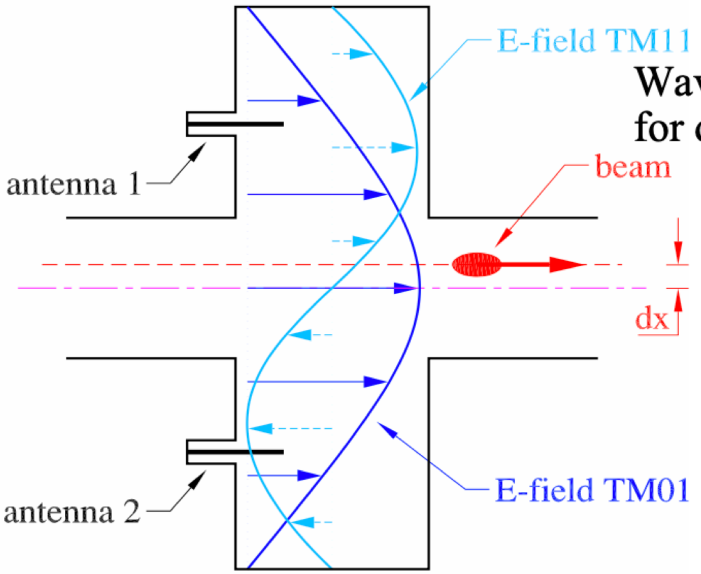
From
M. Wendt (FNAL)

Cavity BPM

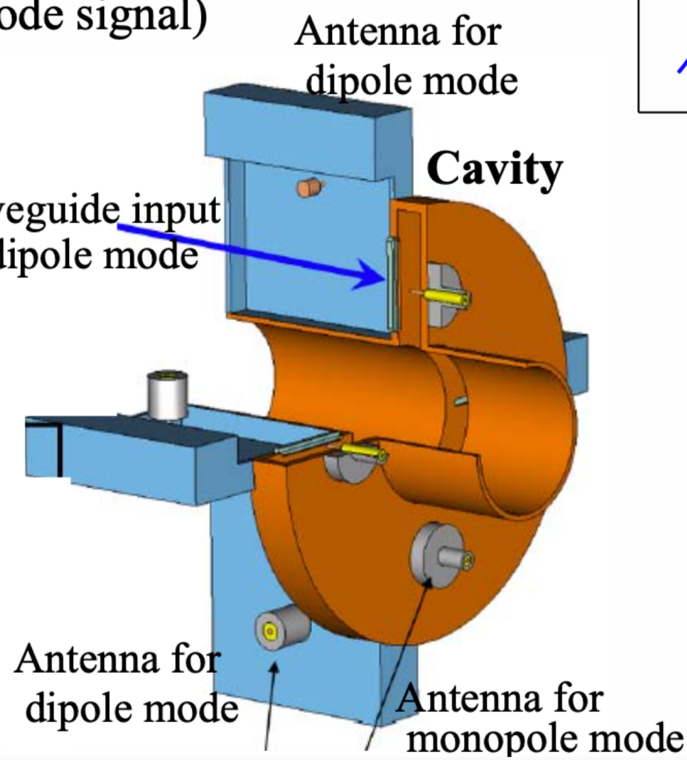
Basic consideration for detection of eigen-frequency amplitudes:

- Monopole mode f_{010} should differ from f_{rf}
- Dipole mode f_{110} separated from monopole mode
  due to finite quality factor $Q \Rightarrow \Delta f = f/Q$
- Waveguide house the antennas
  (task: suppression of TM_{010} mode signal)
- Frequency range $f_{110} \approx 1 \ldots 10$ G





From M. Wendt (FNAL)



FNAL BPM develop.

Cavity: ∅ 113 mm
Gap length 15 mm
Mono. f_{010}=1.12 GHz
Dipole. f_{110}=1.47 GHz
$Q_{load} \approx 600$
With comparable BPM
⇒0.1 μm resolution within 1 μs

Comparison of BPM Types (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Shoe-box	p-Synch.	Long bunches f_{rf}<10 MHz	Very linear No x-y coupling Sensitive For broad beams	Complex mechanics Capacitive coupling between plates
Button	p-Linacs, all e^- acc.	f_{rf}>10 MHz	Simple mechanics	Non-linear, x-y coupling Possible signal deformation
Stipline	colliders p-Linacs all e^- acc.	best for $\beta \approx 1$, short bunches	Directivity 'Clean' signals Large Signal	Complex 50 Ω matching Complex mechanics
Ind. WCM	all	non	Broadband	Complex, long insertion
Cavity	e^- Linacs (e.g. FEL)	Short bunches Special appl.	Very sensitive	Very complex, high frequency

Remark: Other types are also some time used, e.g. inductive antenna based, BPMs with external resonator, slotted wave-guides for stochastic cooling etc.

Summary

- General Idea of BPM

- Several type of BPM
  - Shoe box
  - Button BPM
  - Stripline BPM
  - Cavity BPM

KOREA UNIVERSITY

2022 가속기 및 빔 라인 미래인재
양성 교육단 여름학교

4GSR Beam Diagnostics 3

Korea University
Siwon Jang

01. BPM Electronics

Characteristics for Position Measurement

Sensitivity: Factor between position calculation and signal quantity (Δ/Σ, $\log U_1/U_2$ etc)

Accuracy: Ability for position reading relative to a mechanical fix-point ('absolute position')

- influenced by mechanical tolerances and alignment accuracy
- for cryogenic installations: reproducibility after cryogenic cycles
- by electronics: e.g. amplifier drifts, electronic interference, ADC granularity

Resolution: Ability to determine small displacement variation ('relative position')

- typically: ***single bunch***: 10^{-3} of aperture $\approx$ 100 µm
  averaged: 10^{-5} of aperture $\approx$1 µm, with dedicated methods $\approx$0.1 µm
- in most case much better than accuracy!
- electronics has to match the requirements e.g. bandwidth, ADC granularity…

Bandwidth: Frequency range available for measurement

- has to be chosen with respect to required resolution via analog or digital filtering

Signal-to-noise: Ratio of wanted signal to unwanted background

- influenced by thermal and circuit noise, electronic interference
- can be matched by bandwidth limitation

Dynamic range: Range of beam currents the system has to respond

- position reading should not depend on input amplitude

Signal sensitivity = detection threshold: minimum beam current for measurement

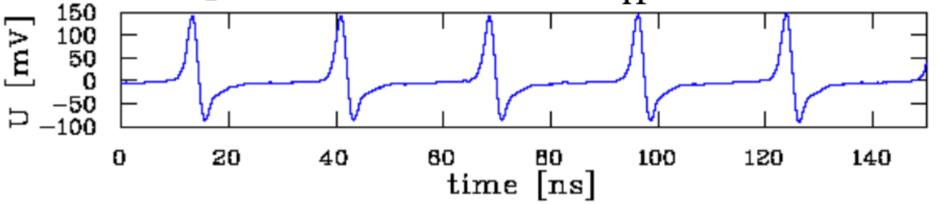
General: Noise Consideration

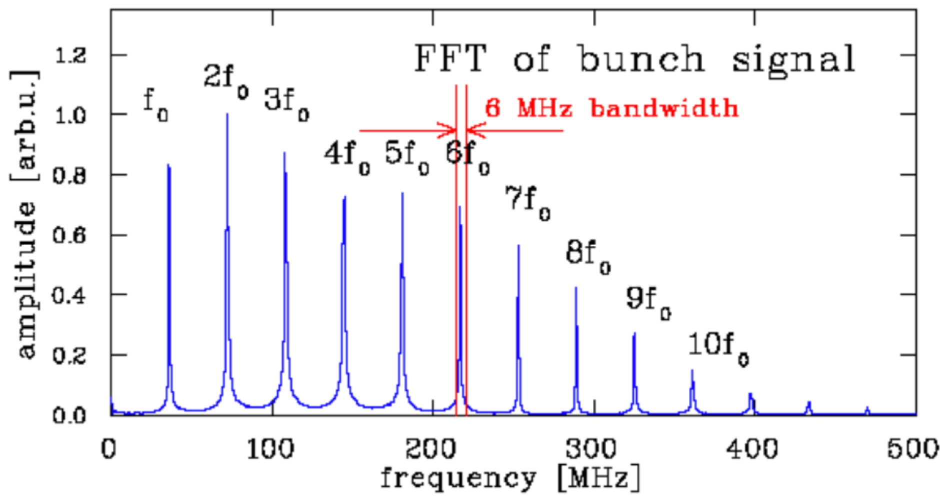
1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$
2. Position information from voltage difference: $x \propto k \cdot U_\Delta$
3. Thermal noise voltage given by: $U_{eff}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$

$\Rightarrow$ Signal-to-noise U_{im}/U_{eff} is influenced by:

- Input signal amplitude
  $\rightarrow$ large or matched Z_t
- Thermal noise at R=50Ω for T=300K
  (for shoe box R=1kΩ …1MΩ)
- Bandwidth Δf
  $\Rightarrow$ Restriction of frequency width because the power is concentrated on the harmonics of f_{rf}

Example: GSI-LINAC with f_{rf}=36 MHz

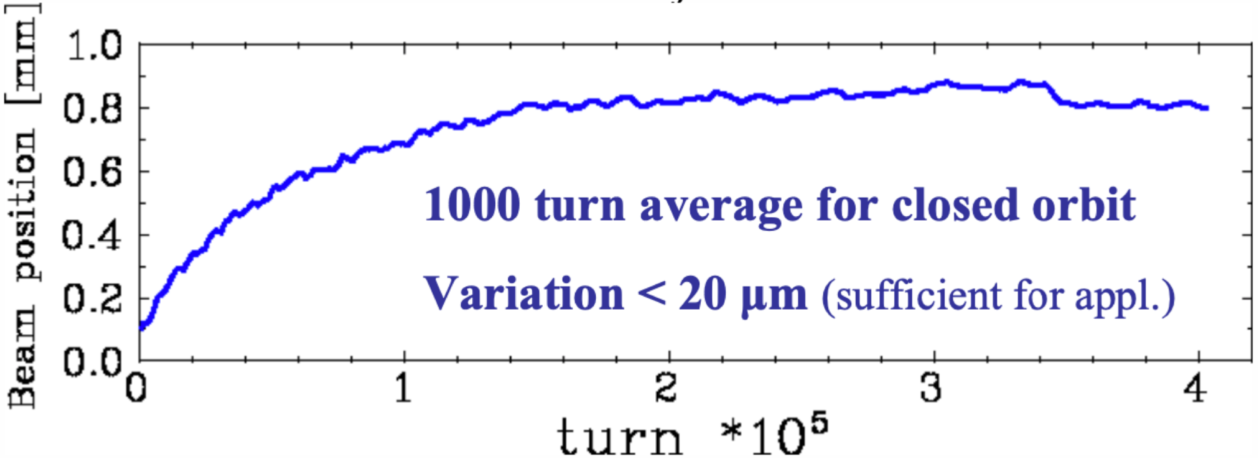




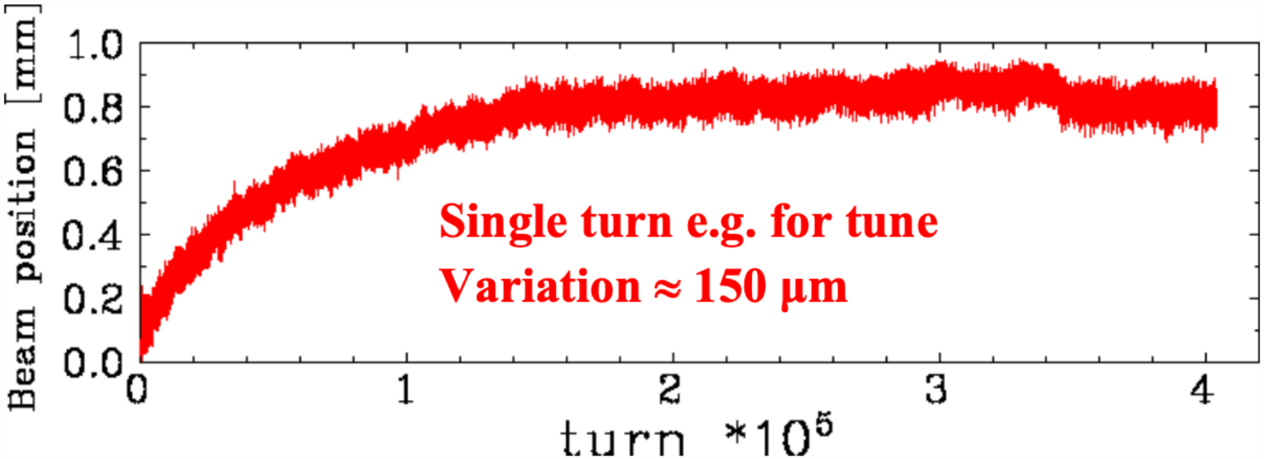
Remark: Additional contribution by non-perfect electronics typically a factor 2
Pick-up by electro-magnetic interference can contribute ⇒ good shielding required

Comparison: Filtered Signal ↔ Single Turn

Example GSI Synchr.: U^{73+}, E_{inj}=11.5 MeV/u→ 250 MeV/u within 0.5 s, 10^9 ions



- Position resolution < 20 µm (BPM half aperture a=40 mm)
- average over 1000 turns corresponding to ≈0.3 ms or ≈1 kHz bandwidth

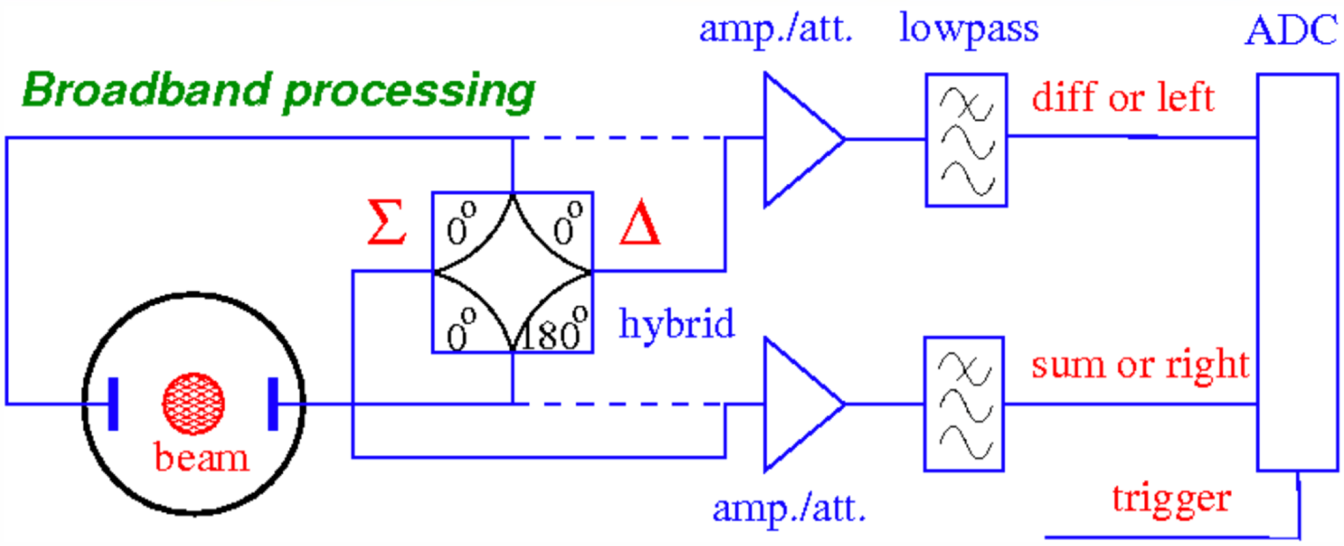


- Turn-by-turn data have much larger variation

However: not only noise contributes but additionally **beam movement** by betatron oscillation

⇒ broadband processing i.e. turn-by-turn readout for tune determination

General Idea: Broadband Processing

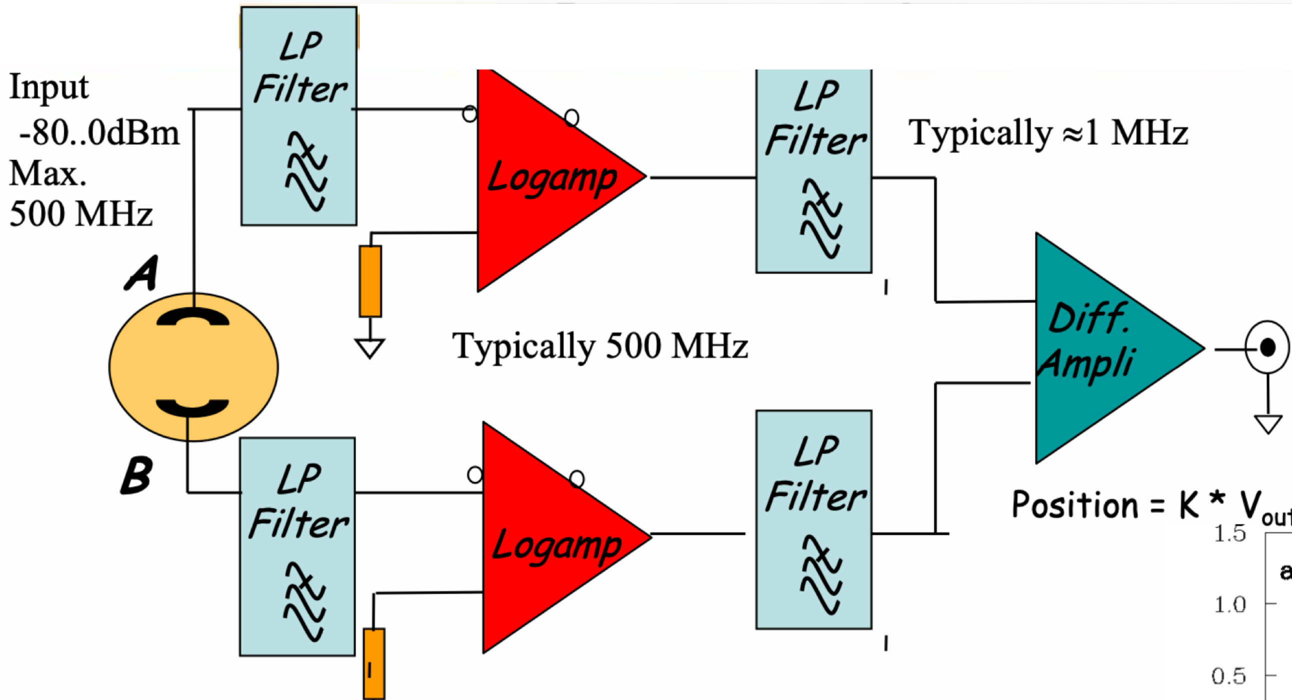


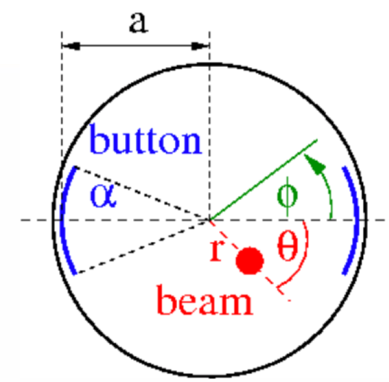
- Hybrid or transformer close to beam pipe for analog U_{Δ} & U_{Σ} generation or U_{left} & U_{right}
- Attenuator/amplifier
- Filter to get the wanted harmonics and to suppress stray signals
- ADC: digitalization of U_{Δ} /U_{Σ} or calculation from U_{left} & U_{right}

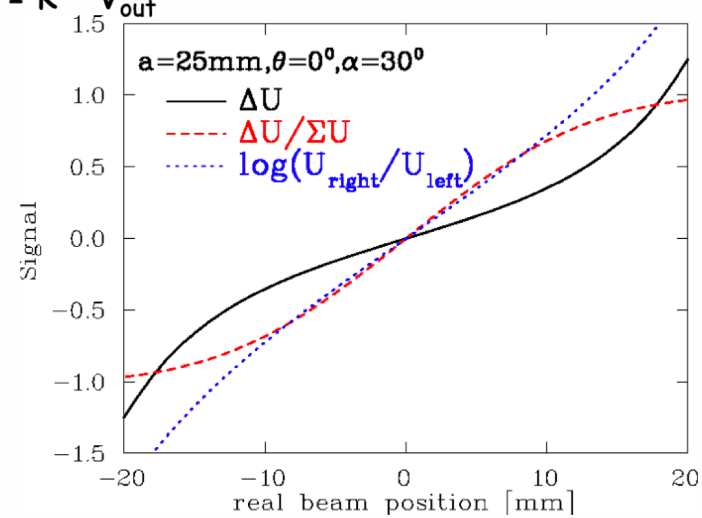
Advantage: Bunch-by-bunch possible, versatile post-processing possible

Disadvantage: Resolution down to ≈ 100 μm for shoe box type , i.e. ≈0.1% of aperture, resolution is worse than narrowband processing.

General Idea: Logarithmic Amplifier Schematics







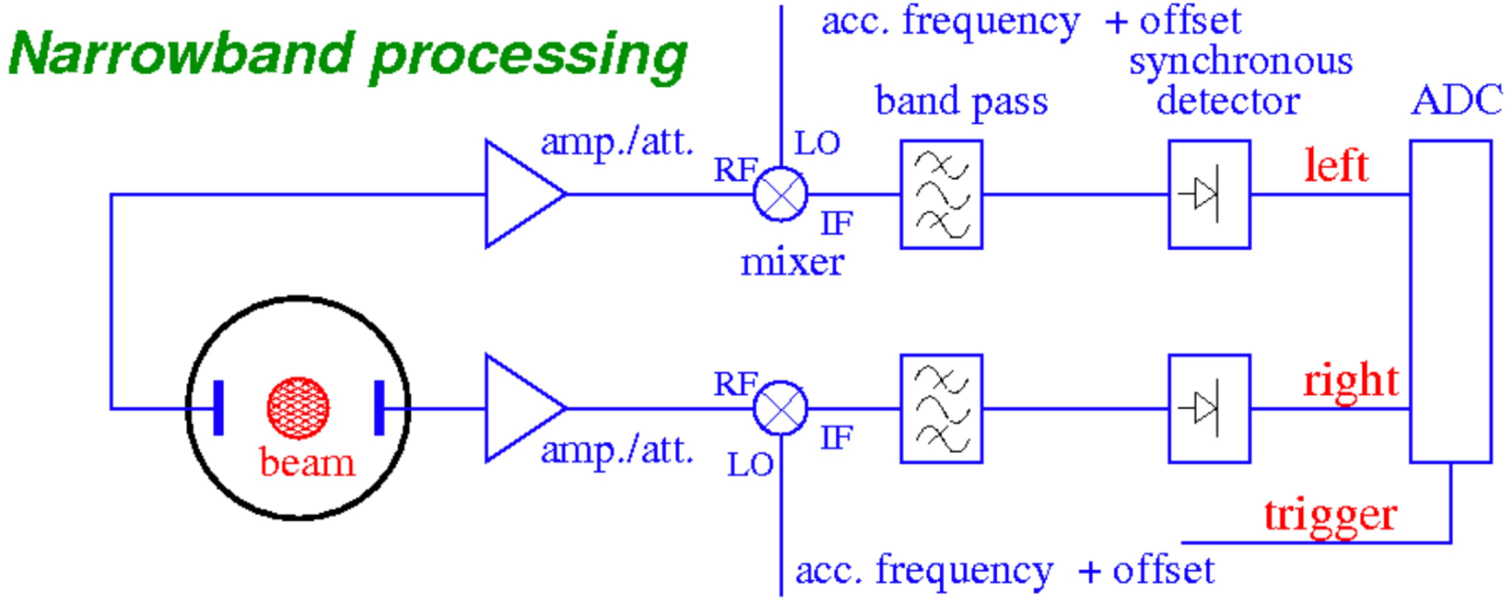
- Signal is 'compressed' by a logarithmic amplifier, filtered and applied to a differential amplifier.
- Typical video bandwidth ≈1MHz
- Position: $x = k\cdot[\log(A/B)] \equiv k\cdot[\log(A)-\log(B)] = k\cdot V_{out}$

Advantage: Improved linearity for button, broadband robust electronics, large ≈90 dB dynamics range without gain switching

Disadvantage: limited linearity and accuracy, possible temperature dependence

Log-amp card ready for BPM use is commercially available!

General Idea: Narrowband Processing



Narrowband processing equals heterodyne receiver (e.g. at AM-radios or spectrum analyzer)

- Attenuator/amplifier
- Mixing with accelerating frequency $f_{rf} \Rightarrow$ signal with sum and difference frequency
- Bandpass filter of the mixed signal (e.g at 10.7 MHz)
- Rectifier: synchronous detector
- ADC: digital calculation of $\Delta U/\Sigma U$

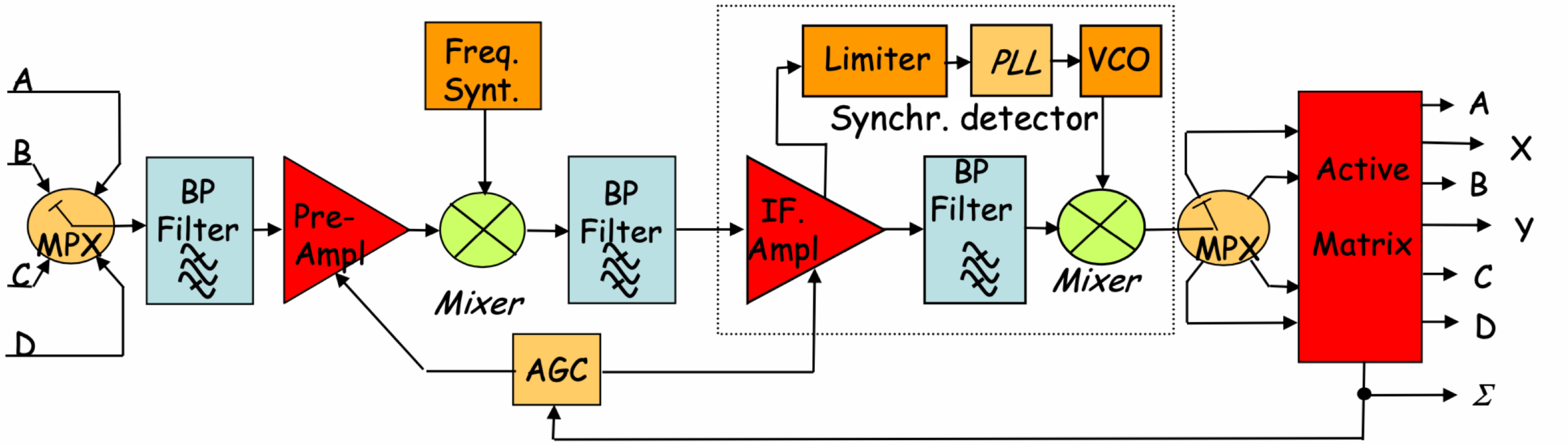
Advantage: spatial resolution about 100 time better than broadband processing.

Disadvantage: No turn-by-turn diagnosis, due to mixing = 'long averaging time'

For non-relativistic p-synchrotron → variable f_{rf} leads via mixing to constant intermediate freq.

Narrowband Processing with Multiplexing

Dedicated analog electronics for narrowband processing on one card (commercially available):



Idea: narrowband processing, all buttons at same path ⇒ multiplexing of single electronics chain

Multiplexing within ≈1ms: ⇒ only one button is processed ⇒ minimal drifts contribution

Processing chain: Buttons → multiplexer → filter → linear amplifier with fine gain steps
→ mixing with f_{rf} → narrow intermediate frequency filter BW 0.1 ….1 MHz
→ synchronous detector for rectification → de-multiplexer → slow and precise ADC

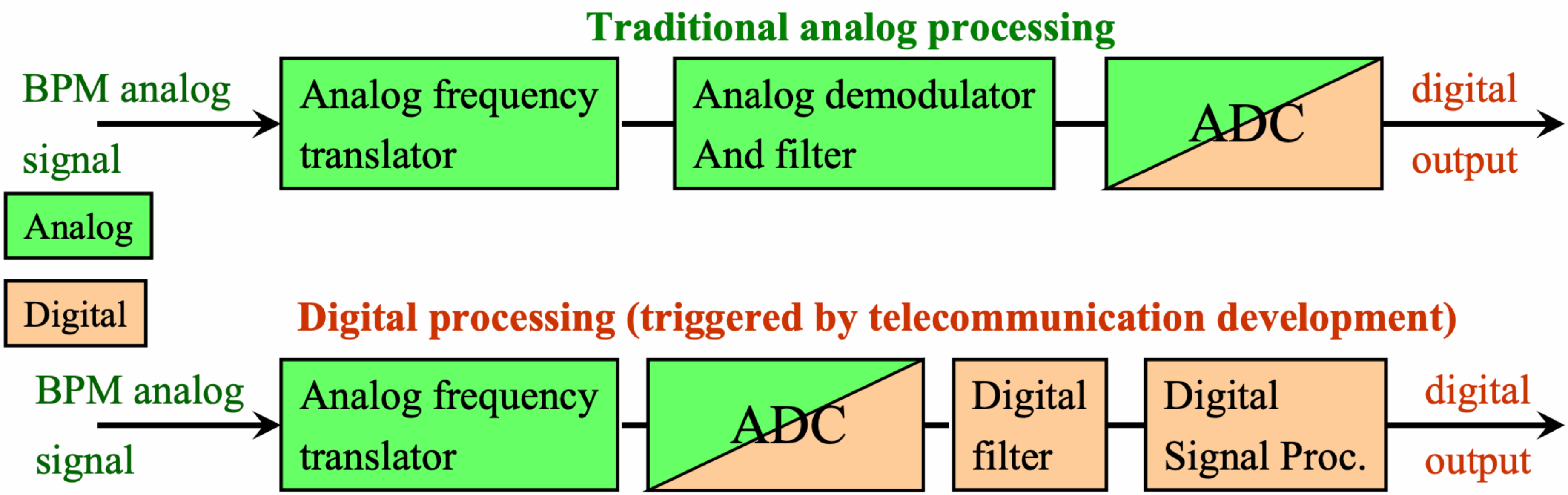
Advantage: High accuracy, high resolution, high dynamic range by automated gain control AGC

Disadvantage: Multiplexing ⇒ only for stable beams >> 10 ms, narrowband ⇒ no turn-by-turn

Remark: 'Stable' beam e.g. at synch. light source, but not at accelerating synchrotrons!

Analog versus Digital Signal Processing

Modern instrumentation uses **digital** techniques with extended functionality.



Digital receiver as modern successor of heterodyne receiver

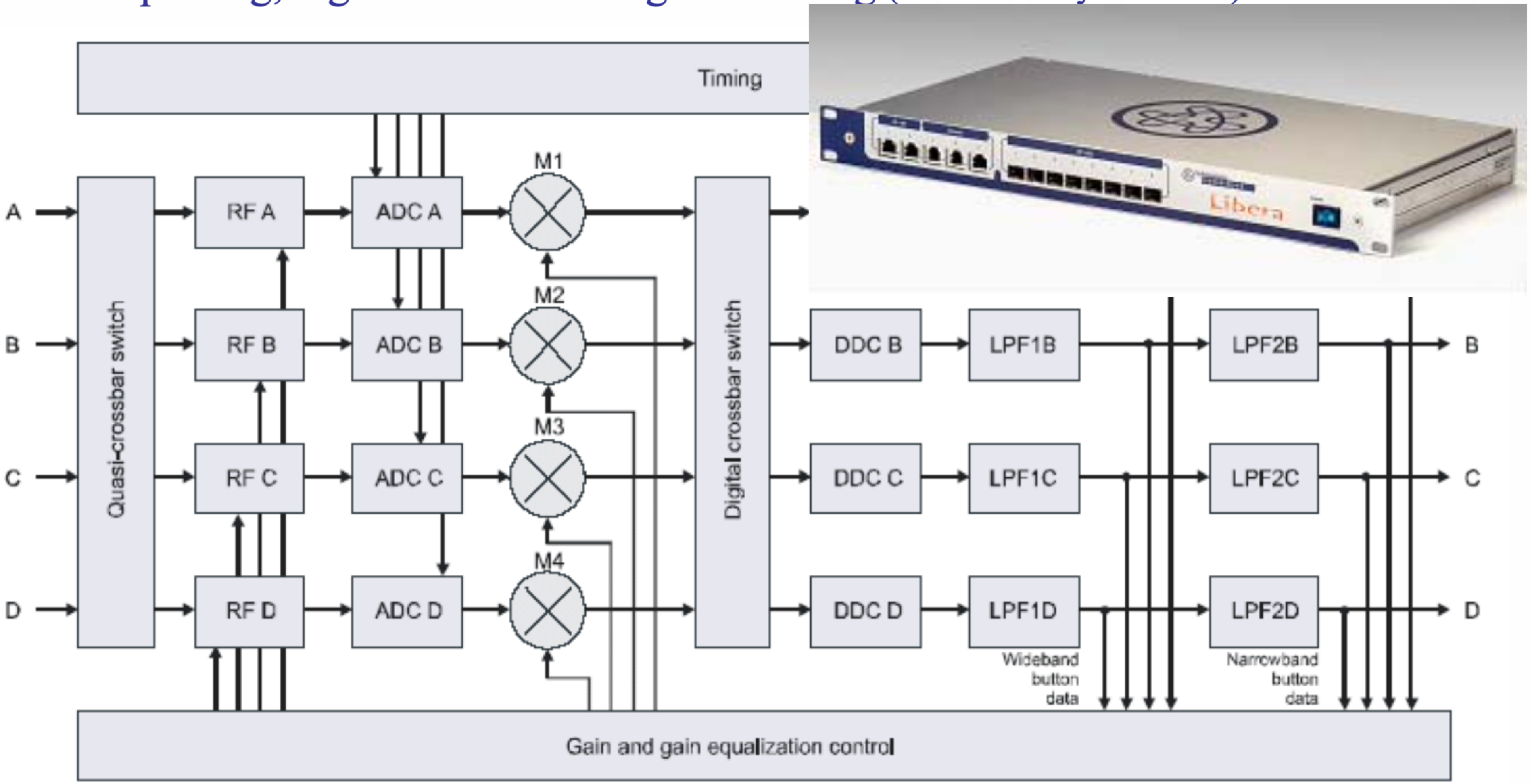
- Basic functionality is preserved but implementation is very different
- Digital transition just after the amplifier&filter or mixing unit
- Signal conditioning (filter, decimation, averaging) on FPGA

Advantage of DSP: Stable operation, flexible adoption without hardware modification

Disadvantage of DSP: non, good engineering skill requires for development, expensive

Digital Signal Processing Realization

Multiplexing, digitalization and digital filtering (commercially available):



From I-Tech LIBERA Specification

LIBERA Digital BPM Readout: Analog Part and Digitalization

Timing for Synchrotron Light Source:

f_{rf}=352 or 500 MHz, revolution $f_{rev}\approx$1 MHz

Crossbar multiplexing of **all** channels at ≈13 kHz (analog)

Automatic gain control by 0…31 dB attenuators

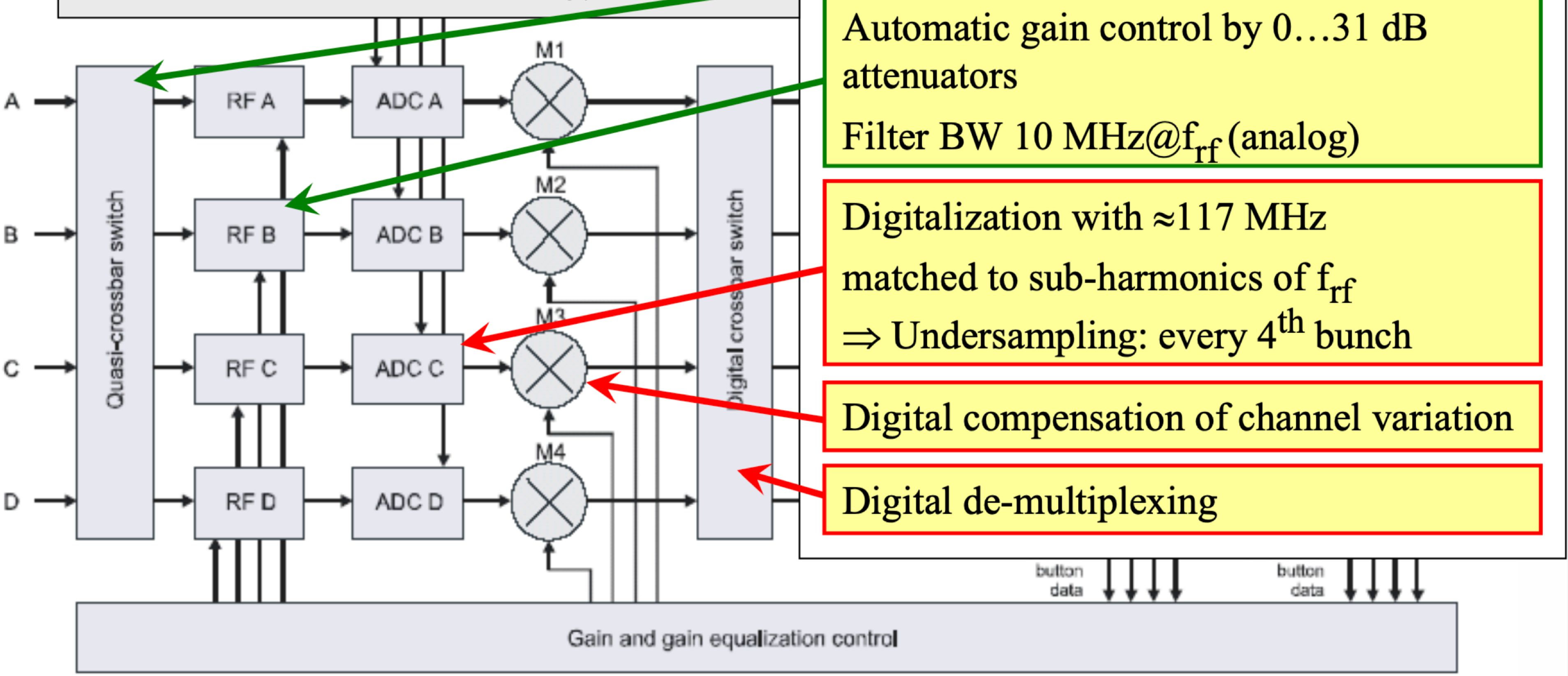
Filter BW 10 MHz@f_{rf} (analog)

Digitalization with ≈117 MHz matched to sub-harmonics of f_{rf}

⇒ Undersampling: every 4^{th} bunch

Digital compensation of channel variation

Digital de-multiplexing



LIBERA Digital BPM Readout: Digital Signal Processing

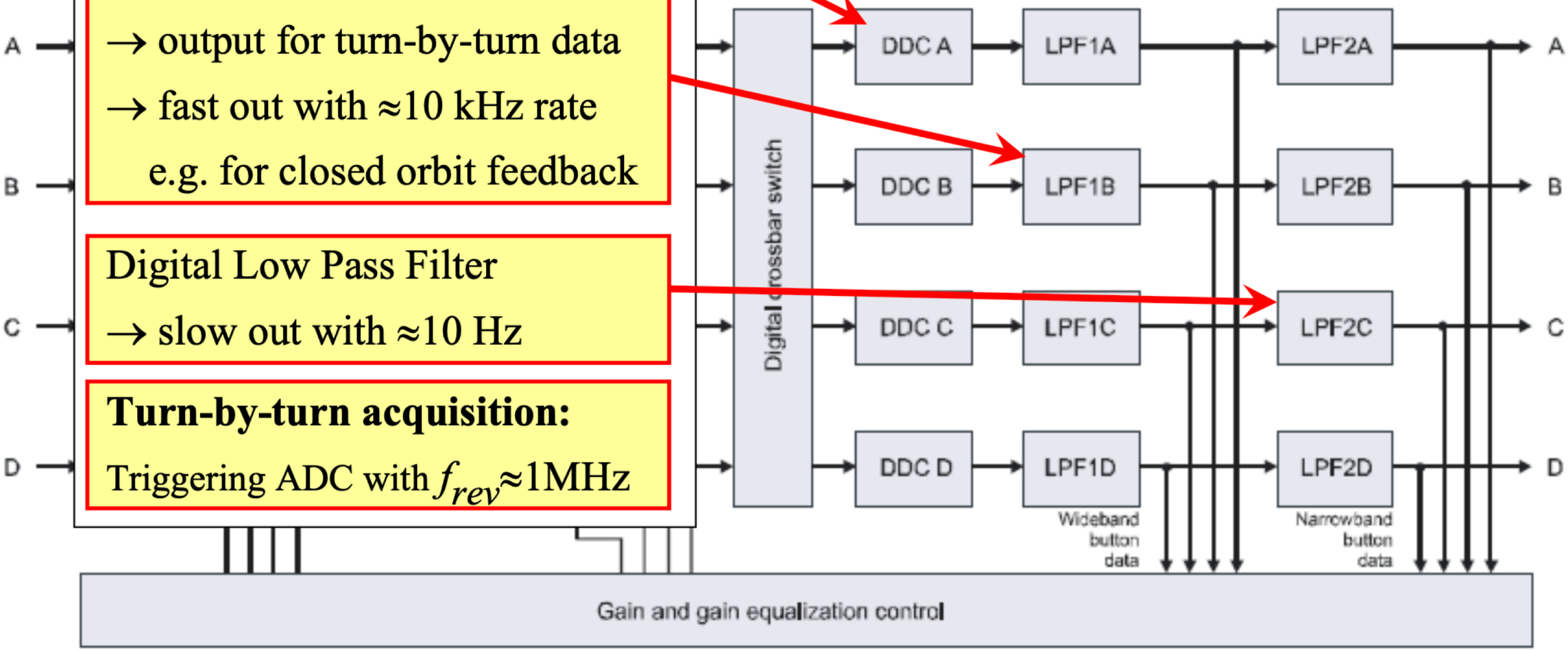
Digital Down Conversion
for data reduction

Digital Low Pass Filter
→ output for turn-by-turn data
→ fast out with ≈10 kHz rate
e.g. for closed orbit feedback

Digital Low Pass Filter
→ slow out with ≈10 Hz

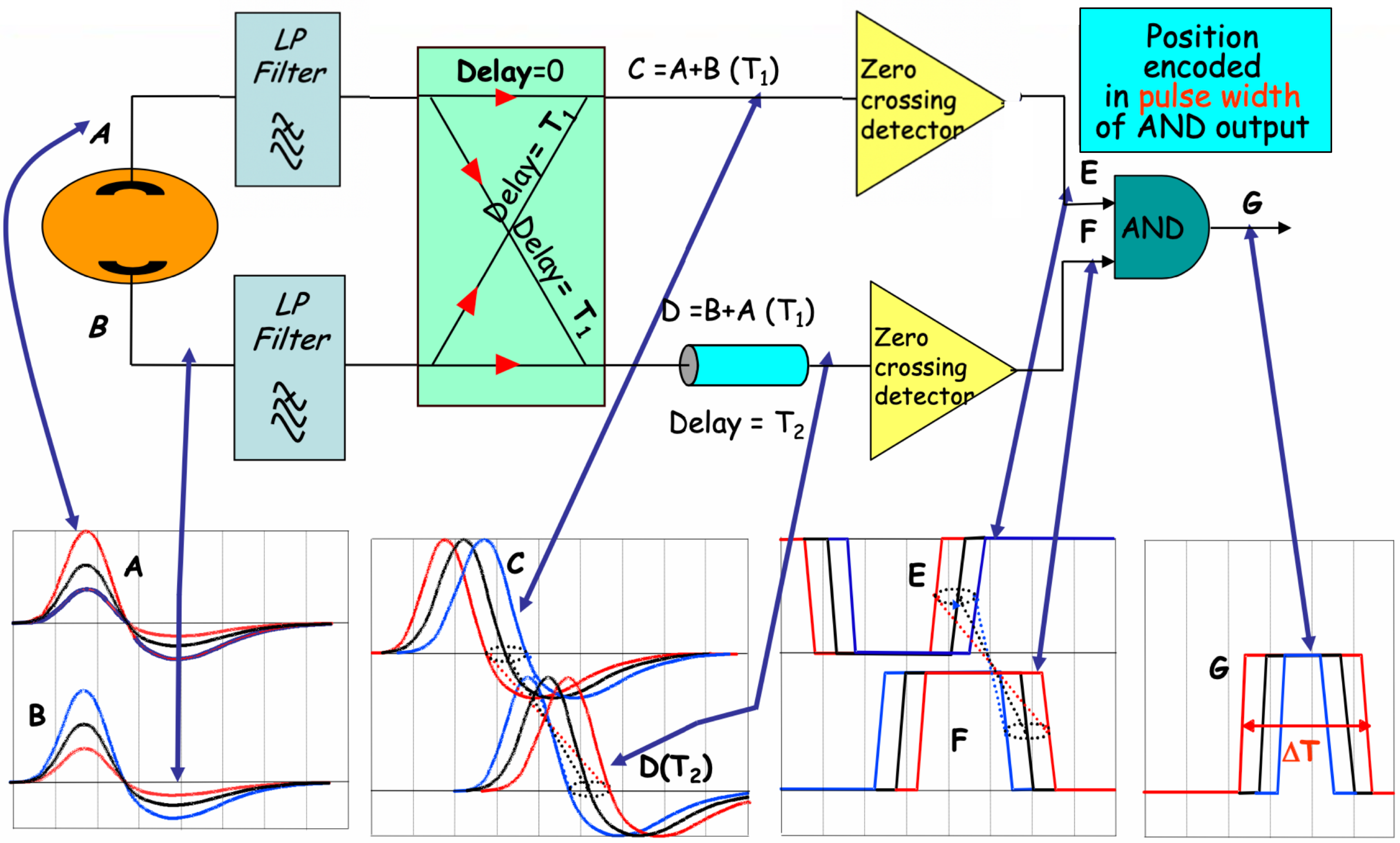
Turn-by-turn acquisition:
Triggering ADC with f_{rev}≈1MHz

Timing for Synchrotron Light Source:
f_{rf}=352 or 500 MHz, revolution f_{rev}≈1 MHz



Remark: For p-synchrotrons direct 'baseband' digitalization with 125 MS/s due to f_{rf}<10 MHz

Amplitude-to-Time Normalizer Schematics



Remark: Design for LHC with f_{rf}=40 MHz and ≈900 locations
Partly comparable to traditional AM/PM modulation

Amplitude-to-Time Normalizer Description

General functionality for Amplitude-to-time Normalizer:

- Bipolar signals A, B are split into two branches
- One branch is delayed by T_1
- The delayed signal of A is added to the direct branch of B and vice versa
- The zero crossing time depends on the signals ratio and varies in opposite directions for two branches; it can vary up to a maximum of T_1
- Zero-crossing detector converts to time $\rightarrow$ start of logical pulse $\Leftrightarrow$ zero crossing
- Delay of channel D by T_2
- AND produces time overlap of channel C and D
- Position information is given by $\Delta t = 2 * T_1\,[(A - B)/(A + B)] + T_2$
- ***Requirement:*** Bunch separation $> T_1 + T_2$

Advantage: reduction of 2 channels and cables, high input dynamics, auto-trigger

Disadvantage: requires specialized and tightly time-adjusted electronics, no intensity signal

Remark:

Comparison of BPM Readout Electronics (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Broadband	p-sychr.	Long bunches	Bunch structure signal Post-processing possible Required for fast feedback	Resolution limited by noise
Log-amp	all	Bunch train >10μs	Robust electronics High dynamics Good for industrial appl.	No bunch-by-bunch Possible drifts (dc, Temp.) Medium accuracy
Narrowband	all synchr.	Stable beams >100 rf-periods	High resolution	No turn-by-turn Complex electronics
Narrowband +Multiplexing	all synchr.	Stable beams >10ms	Highest resolution	No turn-by-turn, complex Only for stable storage
Digital Signal Processing	all	Several bunches ADC 125 MS/s	Very flexible High resolution **Trendsetting technology for future demands**	Limited time resolution by ADC → undersampling (complex or expensive)
Ampl.-to-Time Normal. and AM→PM	(all)	Limited f_{rf} Low bunching factor	Only 2 channels High dynamics	Special electronics No intensity signal A bit exotic

Summary

With BPMs the center in the transverse plane is determined for bunched beams.

Coupling beam → detector given by the transfer impedance $Z_t(\omega)$ signal estimation $I_{beam} \rightarrow U_{im}$

Different type of BPM:

Shoe box = linear cut: for p-synchrotrons with f_{rf}<10 MHz

Advantage: very linear. **Disadvantage:** complex mechanics

Button: Most frequently used at all accelerators, best for f_{rf}>10 MHz

Advantage: compact mechanics. **Disadvantage:** non-linear, low signal

Stripline: Taking traveling wave behavior into account, best for short bunches

Advantage: precise signal. **Disadvantage:** Complex mechanics for 50Ω, non-linear

Cavity BPM: dipole mode excitation → high resolution 1µm@1µs ↔ spatial application

Electronics used for BPMs:

Basics: Resolution in space ↔ resolution in time i.e. the bandwidth has to match the application

Broadband processing: Full information available, but lower resolution, for fast feedback

Log-amp: robust electronics, high dynamics, but less precise

Analog narrowband processing: high resolution, but not for fast beam variation

Digital processing: very flexible, but limited ADC speed, more complex

Resources and References

- Peter Forck: Lecture on Beam Instrumentation and Diagnostics at the Joint University Accelerator School (JUAS),
  see also the extended Bibliography
  http://www-bd.gsi.de/conf/juas/juas.html

- CERN Accelerator Schools (CAS):
  http://cas.web.cern.ch/cas/CAS%20Welcome/Previous%20Schools.htm and
  http://cas.web.cern.ch/cas/CAS_Proceedings.html

  – Rhodri Jones and Hermann Schmickler: Introduction to Beam Instrumentation and Diagnostics, CERN-2006-002.
  – Daniel Brandt (Ed.), 2008 CAS on Beam Diagnostics for Accelerators, Dourdan, CERN-2009-005 (2009).
  – Heribert Koziol, Beam Diagnostic for Acclerators, Univ. Jyväskylä, Finland, CERN 94-01, http://schools.web.cern.ch/Schools/CAS/CAS Proceedings.html (1993).

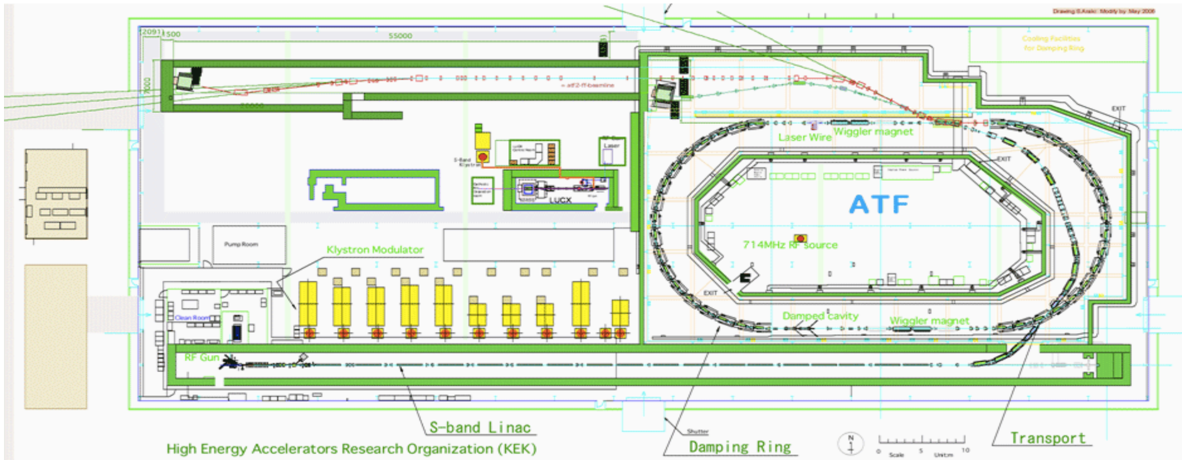
- Jacques Bosser (Ed.), Beam Instrumentation, CERN-PE-ED 001-92, Rev. 1994

2022 가속기 및 빔 라인 미래인재
양성 교육단 여름학교

경청해 주셔서 감사합니다!

Thank you for your attention!

How to decide a BPM type?

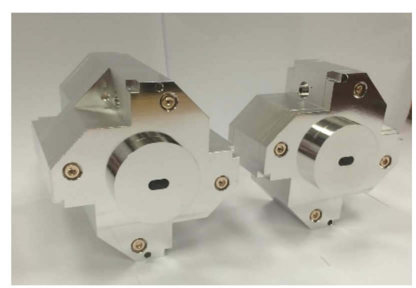


1. LINAC and transport lines vs Synchrotron ?
2. Protons/Ions/electron?
3. Total Beam Energy?
4. Non-destructive or Destructive?
5. How precise, accurate, resolution?
6. Space for installation?
7. Bunch spacing?

1. Beam transport line!
2. Electron!
3. 1.3 GeV!
4. Non-destructive!
5. Nano meter level~! And ns decay time!
6. Inside vacuum chamber!
7. 150ns!

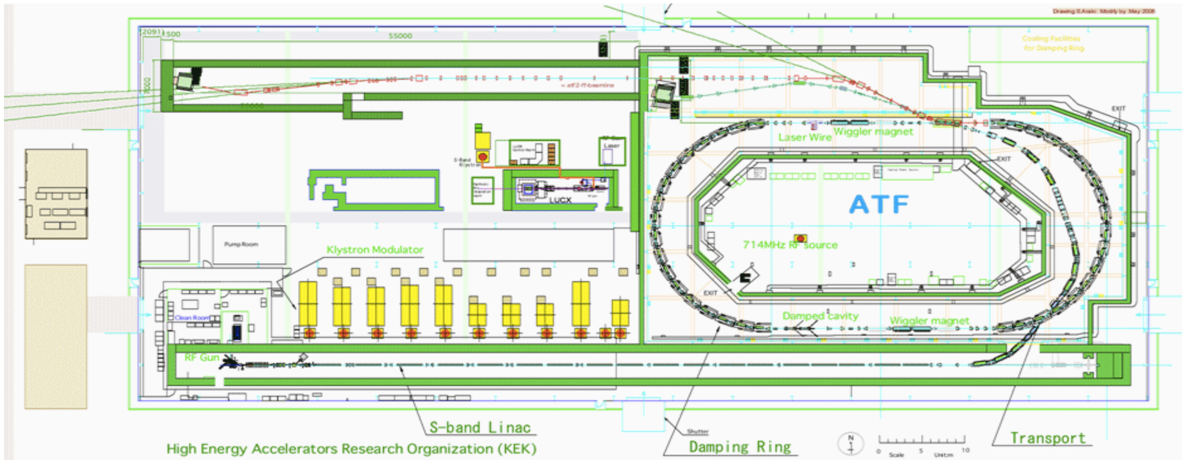
Button
or
Stripline BPM

Or



Cavity BPM

How to decide a BPM type?

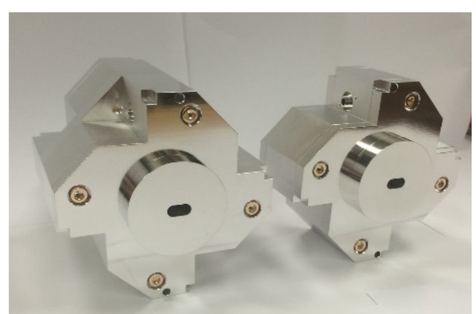


1. LINAC and transport lines vs Synchrotron ?
2. Protons/Ions/electron?
3. Total Beam Energy?
4. Non-destructive or Destructive?
5. How precise, accurate, resolution?
6. Space for installation?

1. Beam transport line!
2. Electron!
3. 1.3 GeV
4. Non-destructive!
5. Nano meter level~! And ns decay time!
6. Inside vacuum chamber!

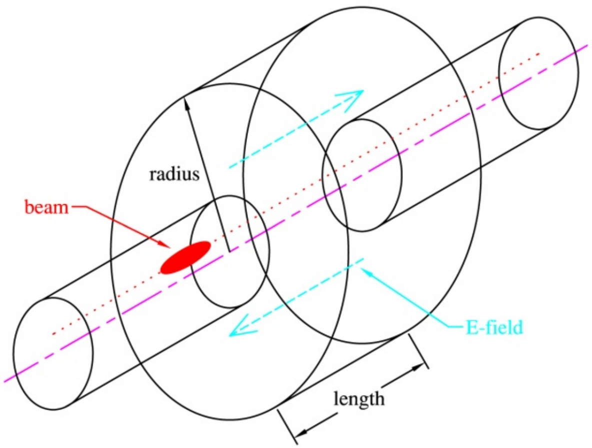
Decision

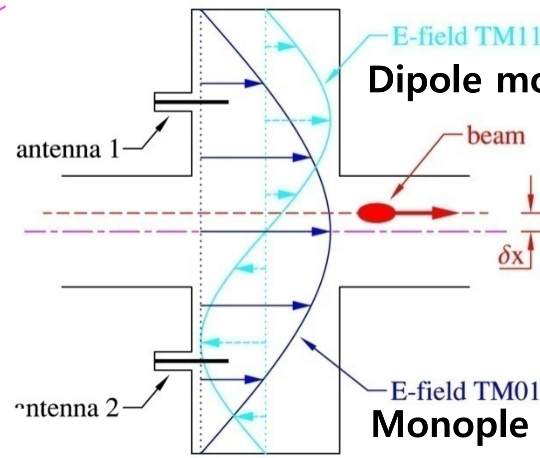
Cavity BPM



Introduction / Cavity BPM

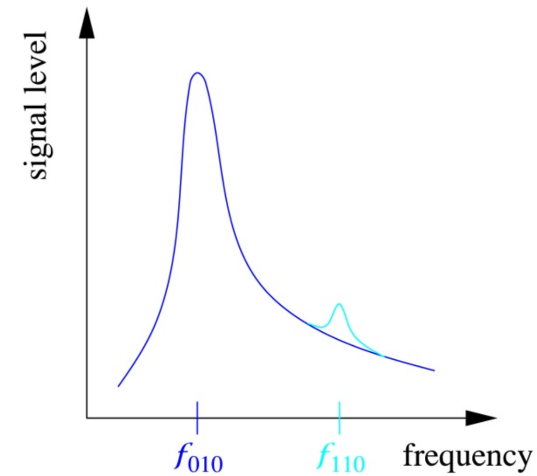
- **Principle** Generates dipole (TM110) and monopole (TM010) modes



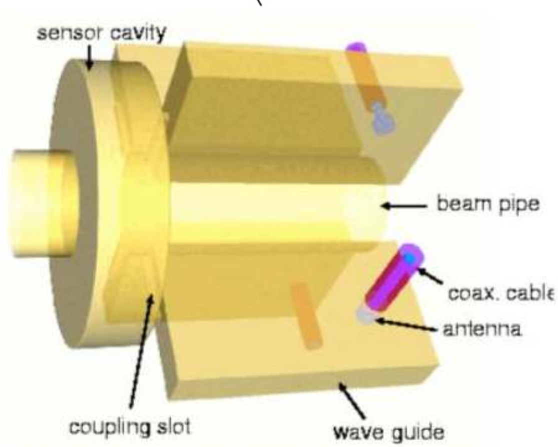


Dipole mode ~ q·δx

Monopole mode ~ q



Needs monopole mode(TM110) suppression!

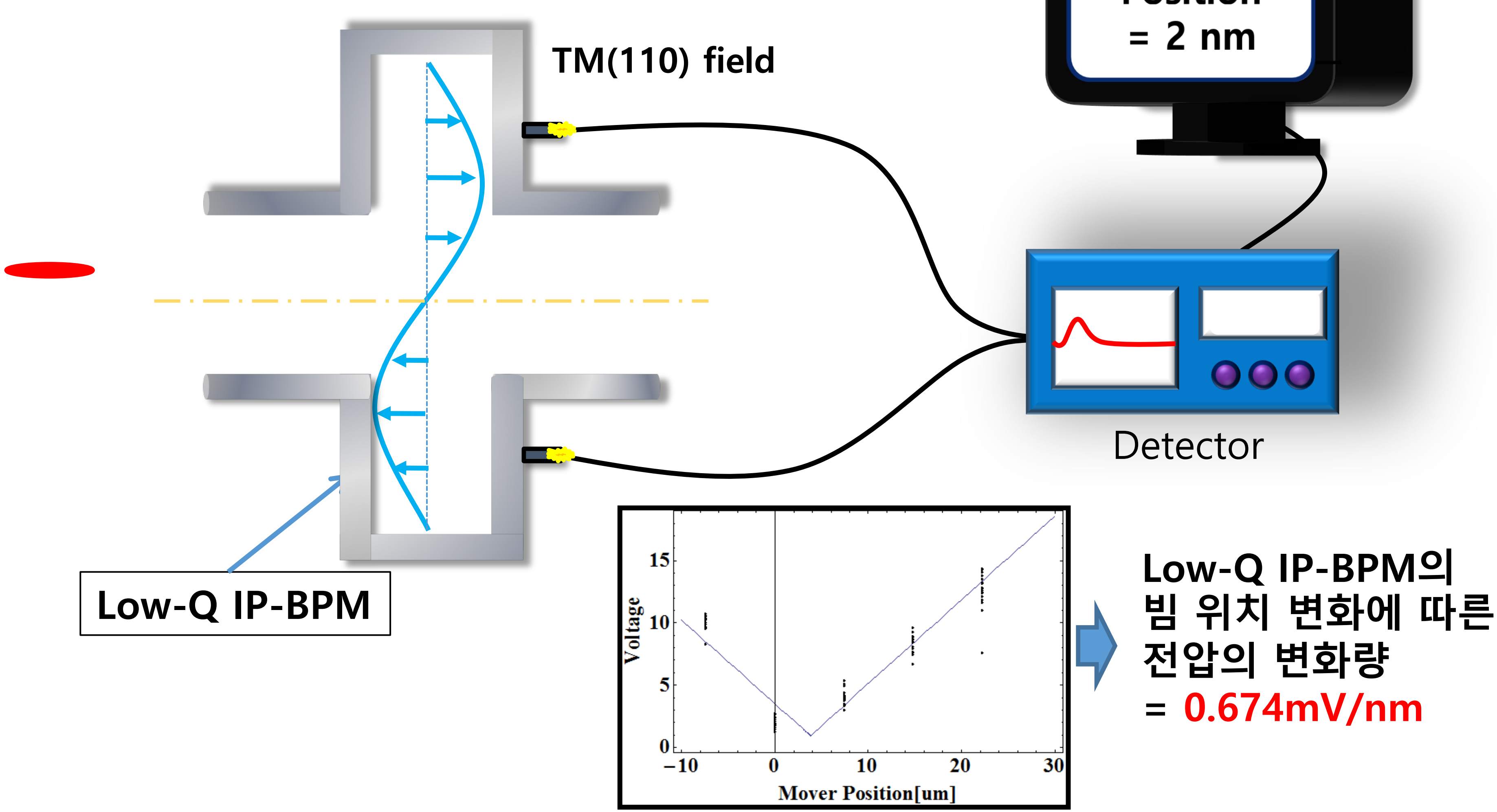


Dipole mode selectable coupler

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

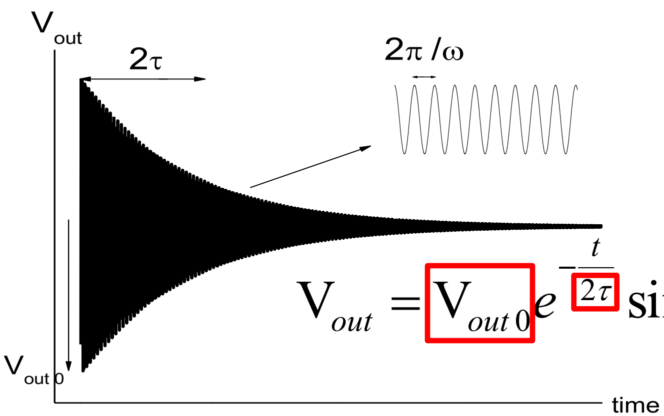
- **Principle of the position measurement**



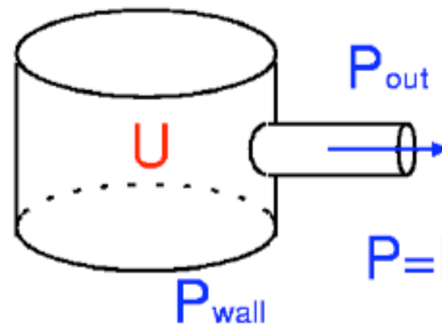
Low-Q IP-BPM의 빔 위치 변화에 따른 전압의 변화량 = 0.674mV/nm

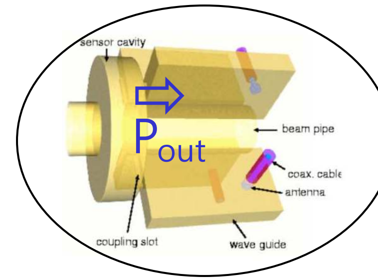
Introduction / Cavity BPM

Parameters for cavity BPM



$$V_{out} = \boxed{V_{out\,0}}\, e^{-\frac{t}{\boxed{2\tau}}} \sin(\boxed{\omega t} + \phi)$$





$P = P_{wall} + P_{out}$

$$Q_0 \equiv \frac{\omega U}{P_{\text{wall}}} \qquad Q_{\text{ext}} \equiv \frac{\omega U}{P_{\text{out}}}$$

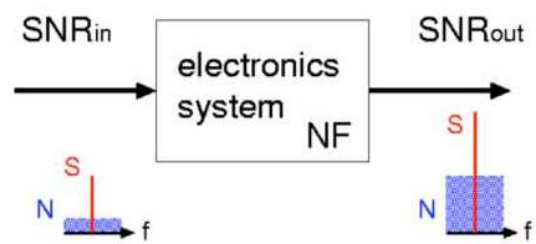
$$\frac{1}{\omega\tau} \equiv \frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \qquad \boxed{Q_L \equiv \frac{\omega U}{P}}$$

S: $V_{out\,0} = \sqrt{ZP_{out}} = \dfrac{\omega q}{2}\sqrt{\dfrac{Z}{Q_{\text{ext}}}(R/Q)}$ ~δx

Where $R/Q = \dfrac{V^2}{\omega U} \qquad V = \int \vec{E} \cdot d\vec{z}$

N: $V_{Th} = \sqrt{4k_b T \cdot BW}$

$$NF = \frac{SNR_{in}}{SNR_{out}}$$



Design of Low-Q IP-BPM

- **The rectangular design is determined since f0 for TM210 or TM120, which is mainly determined by cavity size in X and Y direction, a and b. From simulation and measurements of test cavities, a = 60.88 mm and b = 48.57 mm were determined.**

Parameters	Length[mm]
X direction (= a)	60.88
Y direction (= b)	48.57
Z direction (= L)	5.8
X-beam pipe	12
Y-beam pipe	6

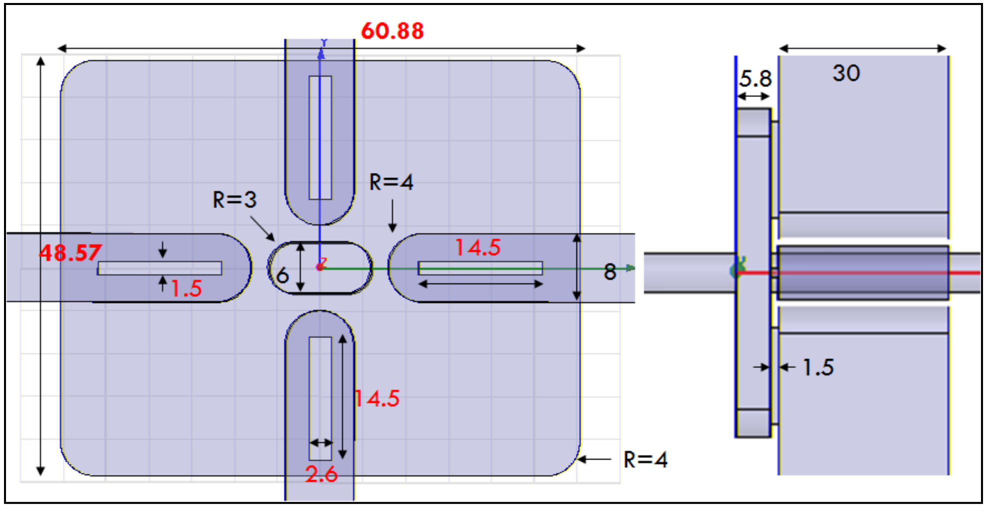
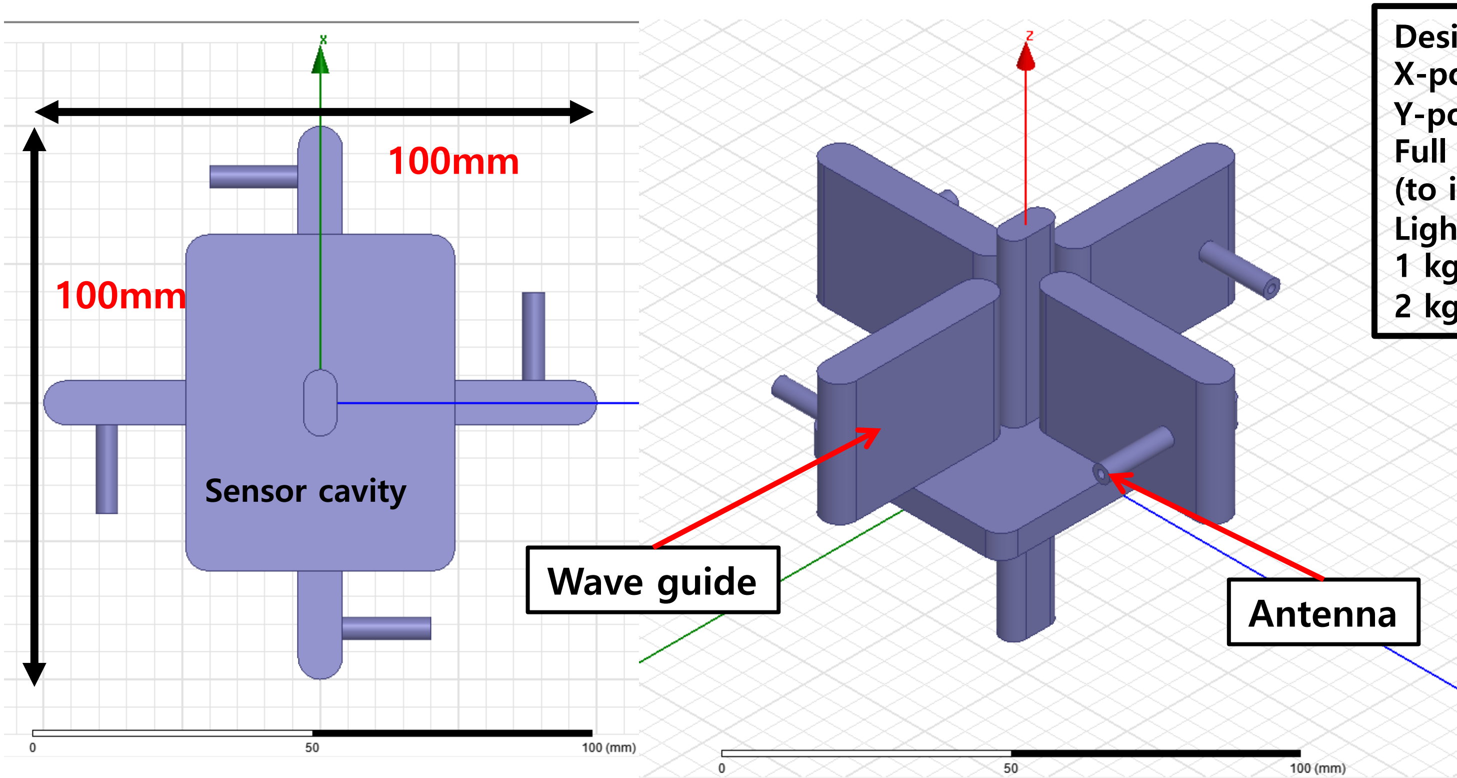


Figure 1: Dimension of cavity

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.

11cm Low-Q IP-BPM design

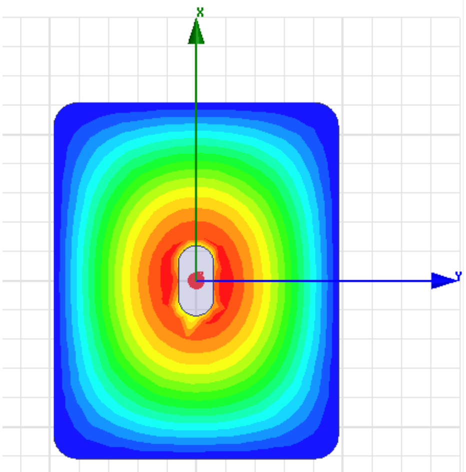
- **11cm Low-Q IP-BPM drawings of HFSS**



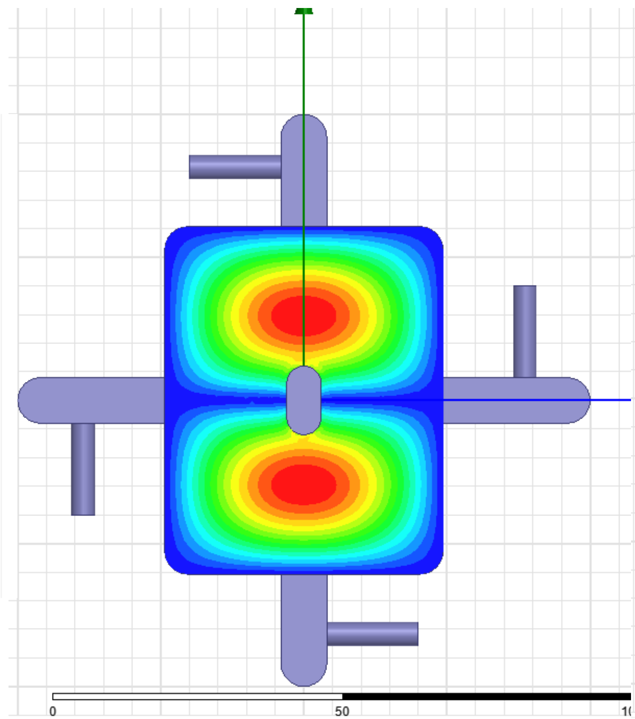
Designed frequency
X-port: 5.712 GHz
Y-port: 6.426 GHz
Full size : 11cmx11cm
(to install IP-Chamber)
Light weight:
1 kg (Single)
2 kg (Double)

11cm Low-Q IP-BPM sensor cavity design

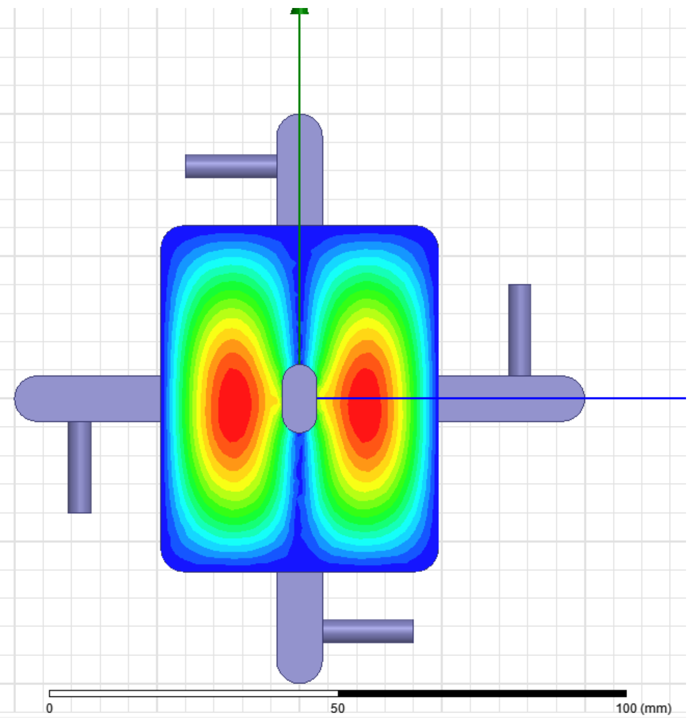
- **Electric field mapping of HFSS simulation**



Mono-pole mode
:3.9808 GHz



X-dipole mode
:5.7127 GHz



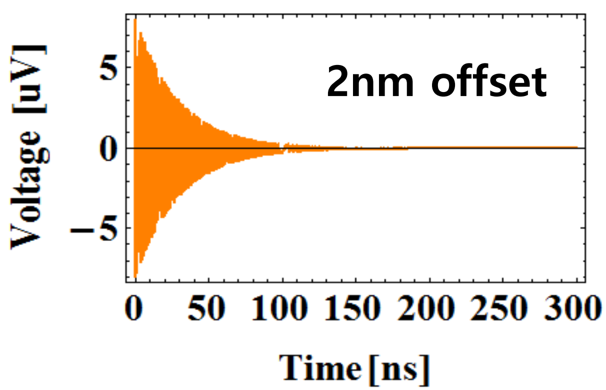
Y-dipole mode
: 6.4280 GHz

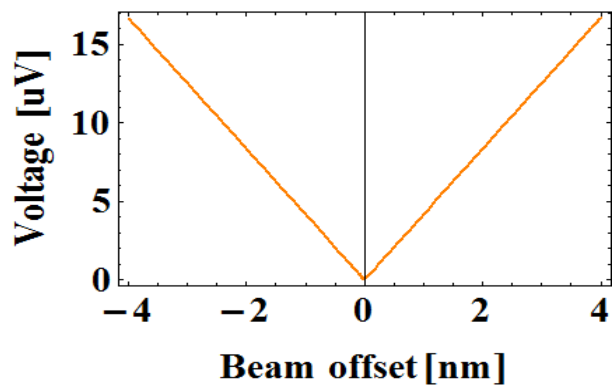
Results of HFSS simulation

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.)

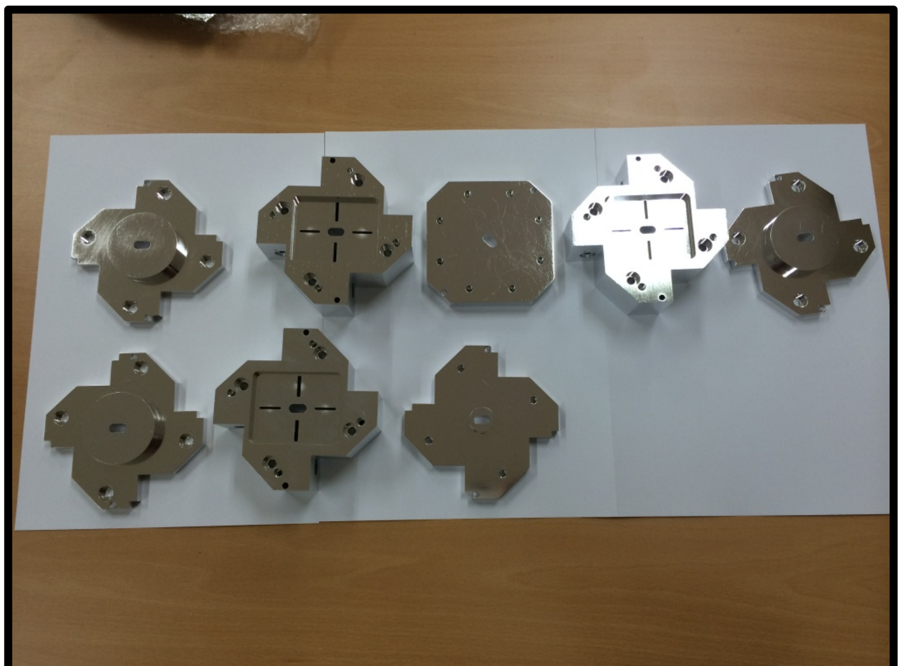


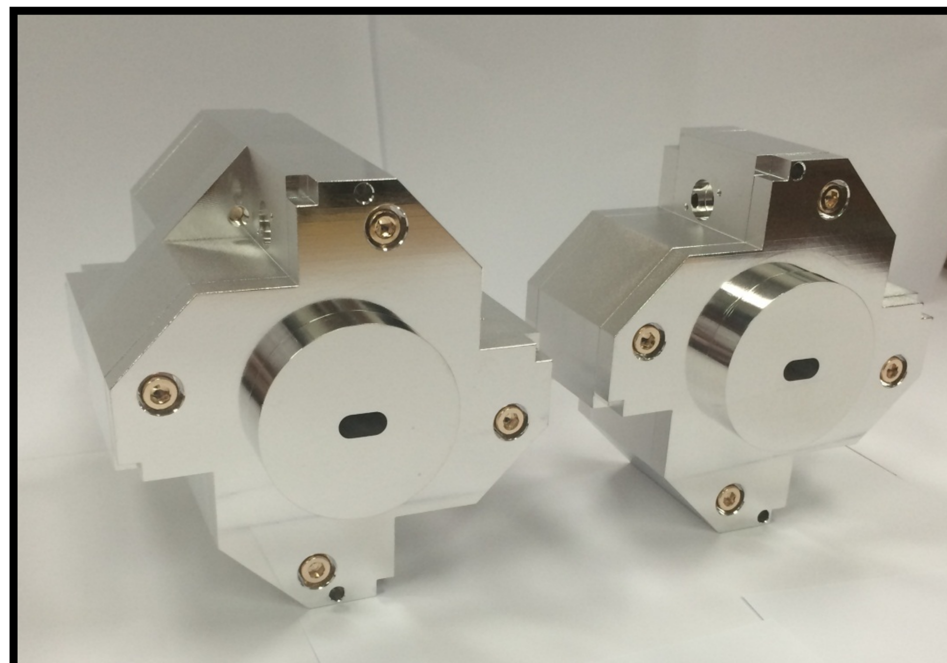


Paramete r	Value	Unit
q (charge)	~ 1.6	nC
Beam energy	1.3	GeV
Bunch length	8	mm

Tested Double block IP-BPM

- **Made by Aluminum** (2kg for double block)
  - Precise surface machining within 4um.





IP-BPM RF measurement

	Port	f_0	β	Q	Q	Q	τ (ns)	V_out (uV/2nm)
Designed	Y-port	6.4280	5.684	4670.43	821.61	698.70	17.23	7.448
Double_1	Y-port	6.4099	0.668	845.66	1266.7	507.11	12.59	6.010
IP-BPM A	Y-port	6.4079	1.140	1231.64	1079.99	575.42	14.29	6.362
Double_2	Y-port	6.4097	0.641	834.70	1302.5	508.70	12.63	5.927
IP-BPM B	Y-port	6.4080	1.268	1188.69	937.154	524.02	13.02	6.829
Single_1	Y-port	6.4089	0.986	1238.0	1255.9	623.43	15.48	6.037
IP-BPM C	Y-port	6.4075	1.206	1318.40	1093.43	597.71	14.85	6.323

:Previous measurements results (6.4095GHz)

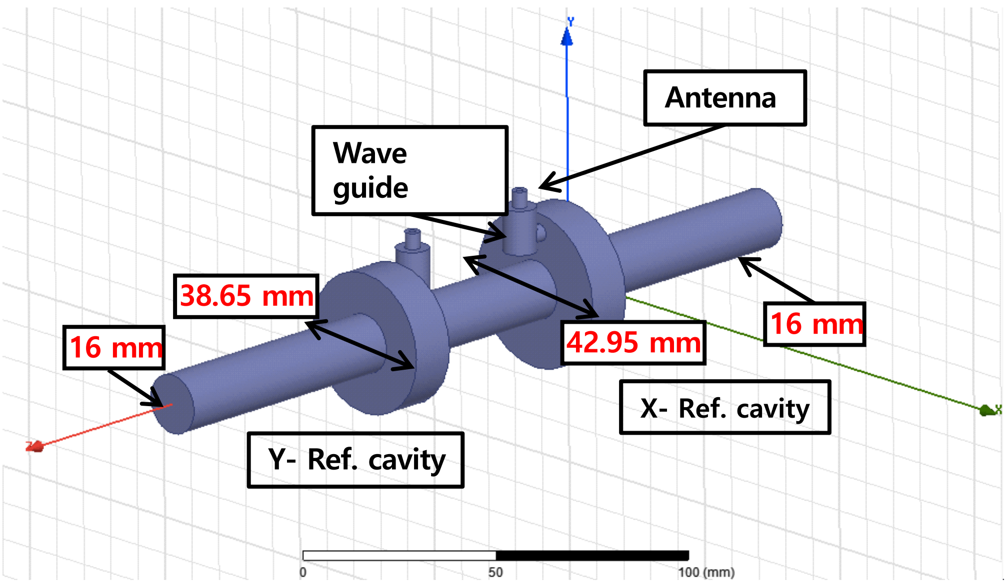
:Re-measurements results in the IP-chamber at July 2013

Average frequency: Y-port 6.4078GHz → The reference cavity frequency!

The Average voltage was 6.248uV/2nm that means 3.124uV/nm for 1.6nC! However, we only used 1-port signals so that the out voltage correspond to 1.562uV/nm for 1.6nC!

Reference cavity BPM design

- Cavity shape for HFSS simulation

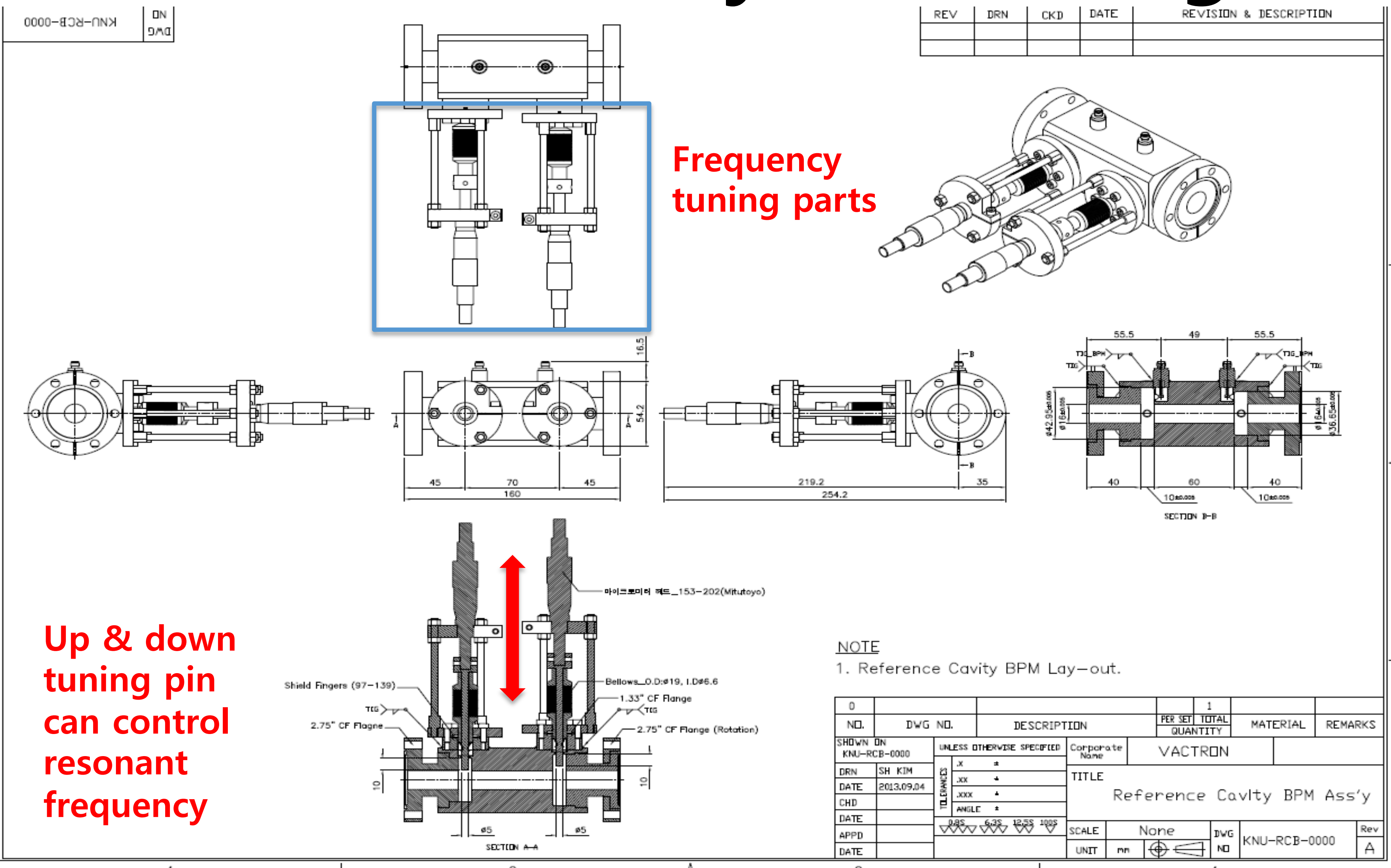


- Cavity size : 42.95mm, 38.65mm
- Beam Pipe radius: 8 mm (circular pipe)
- Material of BPM: Stainless steel (SUS304)

Output signal strength = 22 ~ 5dB (1.6nC ~ 0.32nC)
This output strength too strong to connect LO input. So, we add 20dB attenuator.

Port	f_0 (GHz)	Aim f_0	β	Q_0	Q_{ext}	Q_L	τ (ns)
X-port	5.7107	5.6978	0.00964	1201.20	124578	1189.73	33.157
Y-port	6.4148	6.4078	0.01528	1228.83	80421.2	1210.34	30.029

Reference cavity BPM design

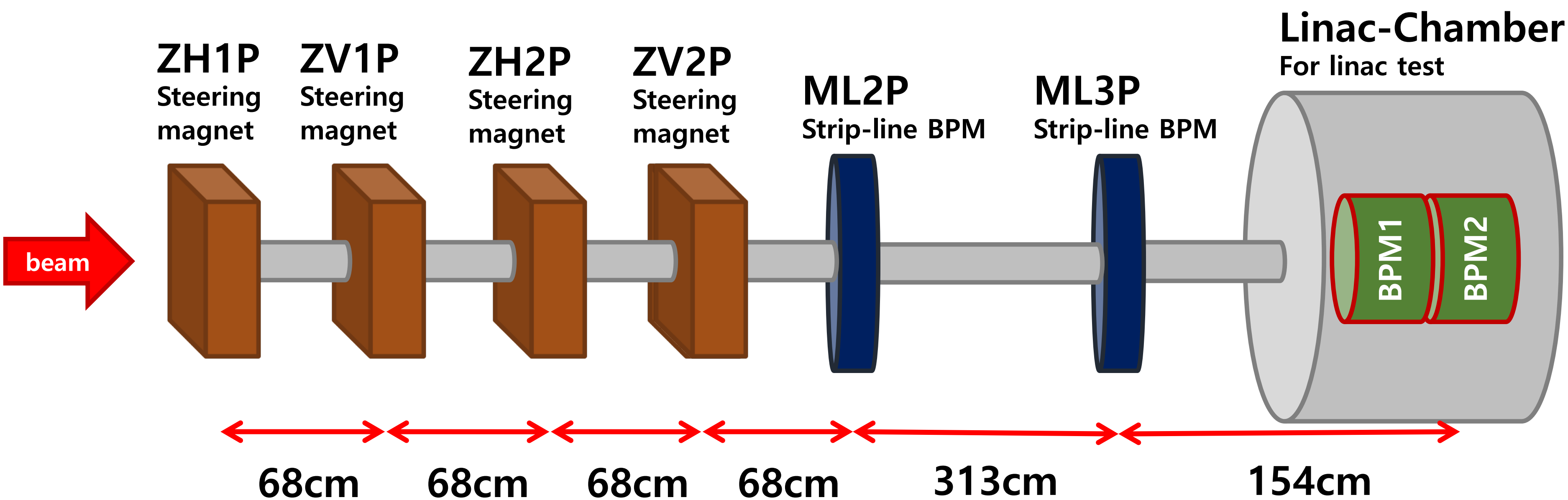


Frequency tuning parts

Up & down tuning pin can control resonant frequency

Test scheme @ end of Linac

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

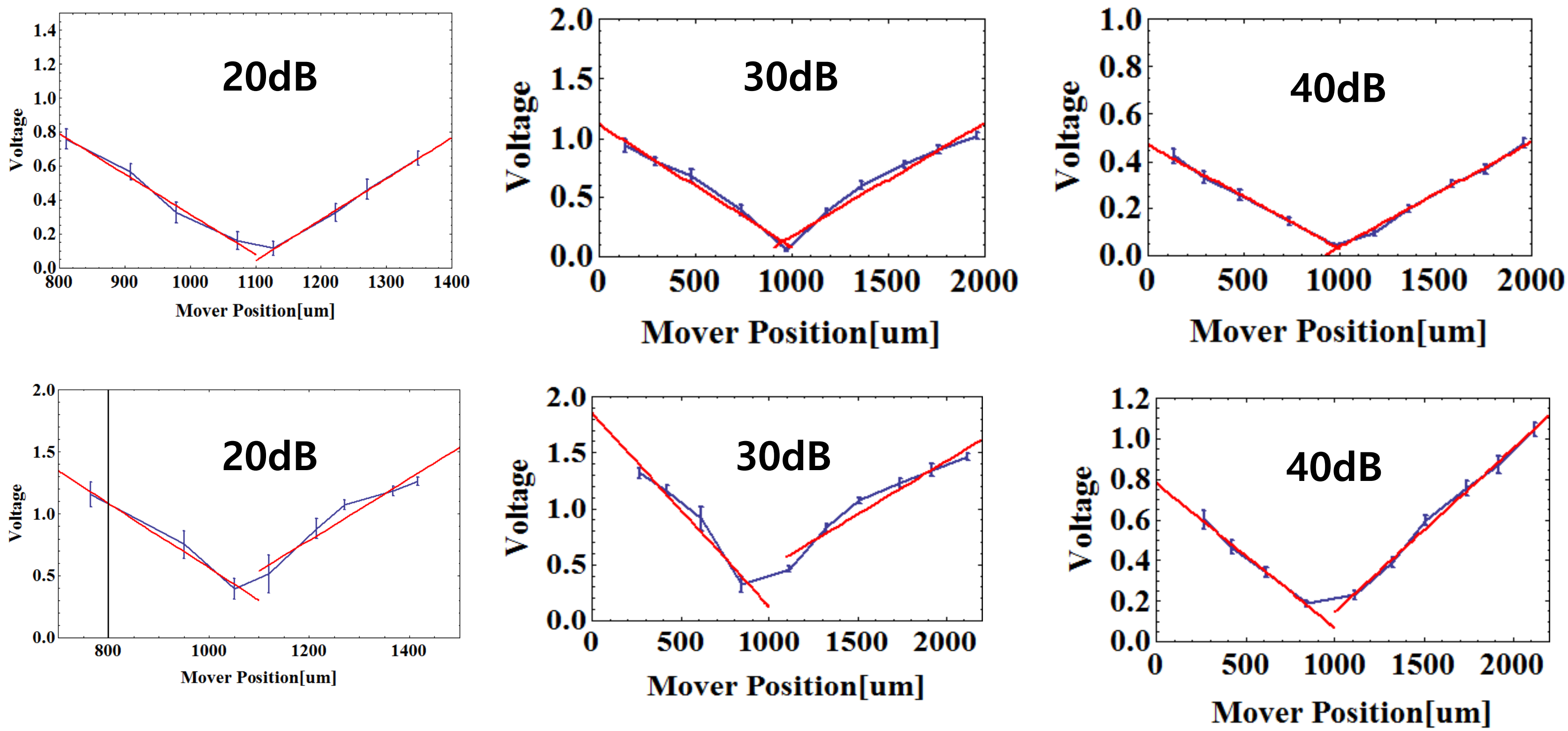


Results of Nov. beam test

- **Calibration Run was made under 40 dB, 30 dB, 20 dB attenuation cases. This is to enlarge dynamic range of the electronics, in order not to saturate while sweeping the beam.**

BPM1 Y-port

BPM2 Y-port



Results of IP-BPM y-port sensitivity At November beam test

- **IP-BPM sensitivity**

(For y-port)

= **2.2558**[mV/um]

(one-port measurements of BPM1)

= **2.22996**[mV/um]

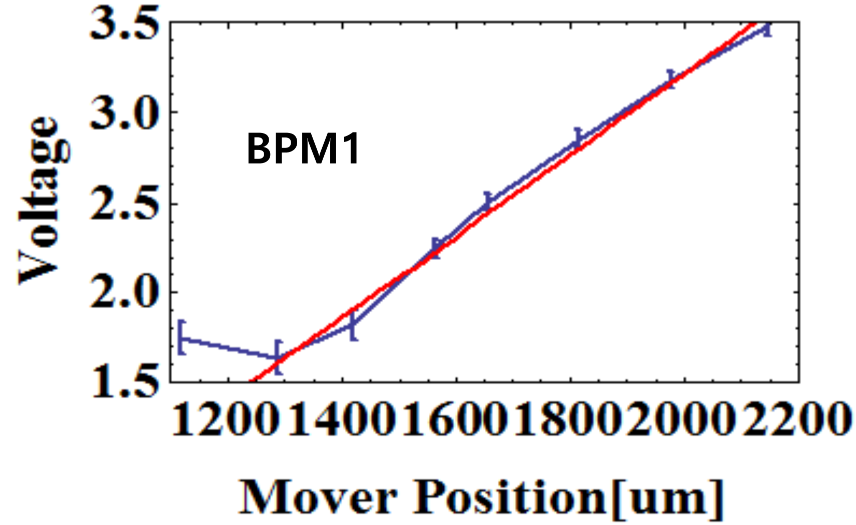
(one-port measurements of BPM2)

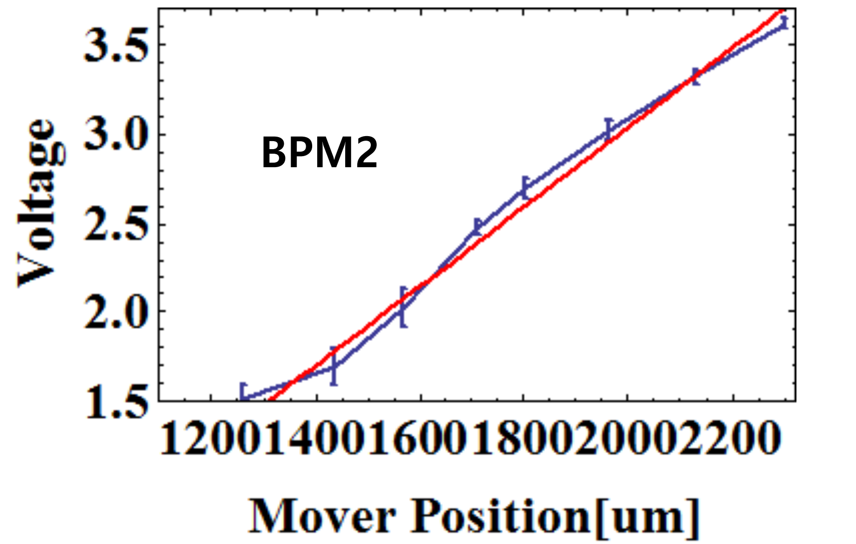
- **Designed sensitivity**

= **3.005** [mV/um] (BPM1)

= **2.964** [mV/um] (BPM2)

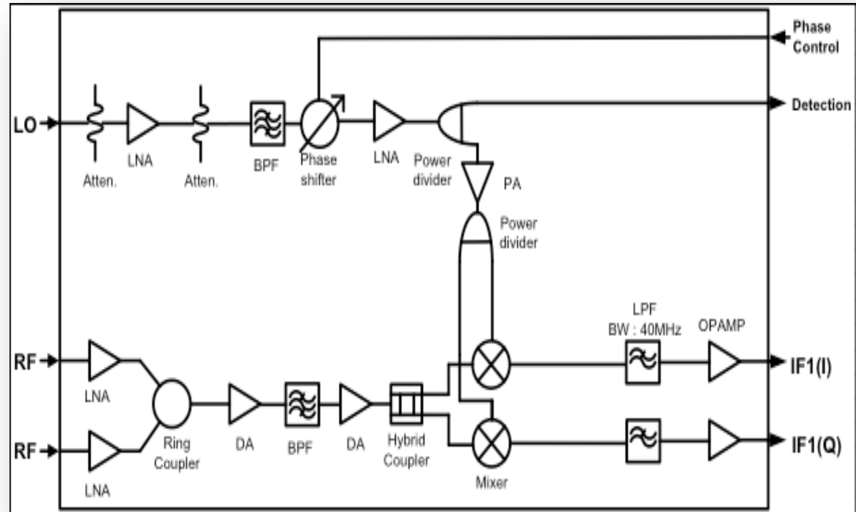
ICT monitor: 0.36~0.38 *10^10 (at LNE)

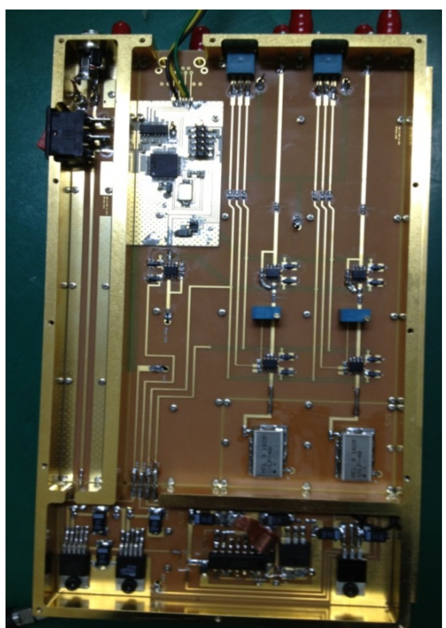




IPBPM electronics Specification

Stage	Function	Gain [dB]	NF [dB]	P1dB [dBm]	Power	Part #	I [mA]
1	Ring Coupler	-3.0	3.0	100000000	-63.0	MS	
2	LNA	19.0	1.8	15	-44	HMC902LP3E	80
3	Ring Coupler	-3.0	3.0	100000000	-47	MS	
4	DA	19.0	1.8	15	-28	HMC902LP3E	80
5	Attem / Filter	-3.0	3.0	100000000	-31		
6	DA	19.0	1.8	15	-12	HMC902LP3E	80
7	Hybrid	-3.0	3.0	100000000	-15	MS	
8	Mixer	-7.0	7.0	0	-22	HMC129LC4	
9	LPF	-1.0	1.0	100000000	-23	SXLP-40+	
10	OPAMP	16.0	15.0	100000000	-7	OPA847	40
	Total Gain	**53.0**	**4.88**		-7	Toal Current	**280**

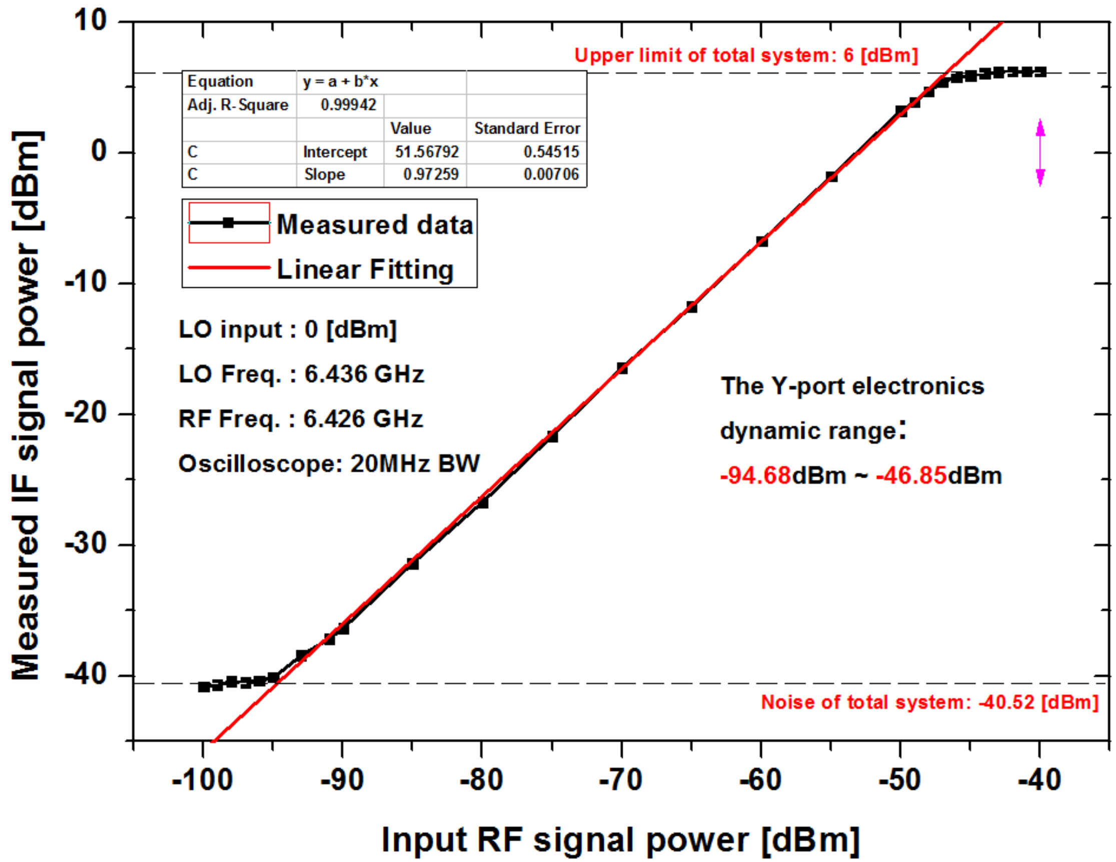




	KNU Electronics
BW of LPF	40MHz
Gain	54dB~ 45dB
Thermal Noise (by calculation)	-96dBm
Estimated Resolution due to thermal noise	1nm
Cascaded NF	1.88dB
Estimated Resolution considering NF	1nm (NF 1.88dB)
Estimated Latency	25ns

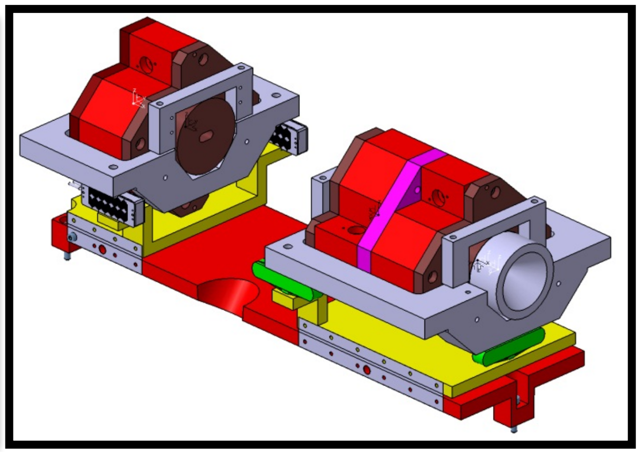
Y-port electronics linearity test

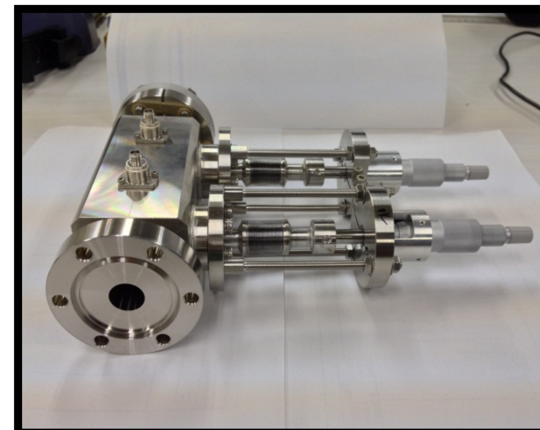
- The IPB-Y electronics performance was checked. The linearity test was performed due to different RF input power. The linear range for Y-port electronics was checked from -94.68dBm to -46.85dBm.
- The conversion gain was measured from 53 to 54dBm within RF working range.

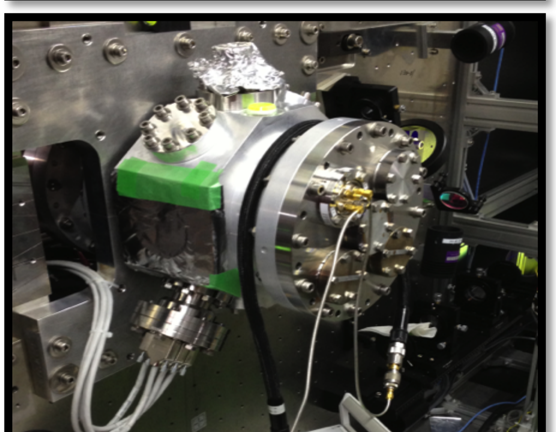


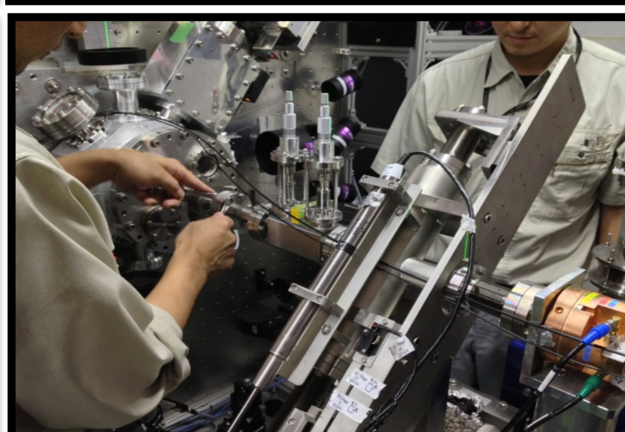
Installation of IP-BPM system with alignment check

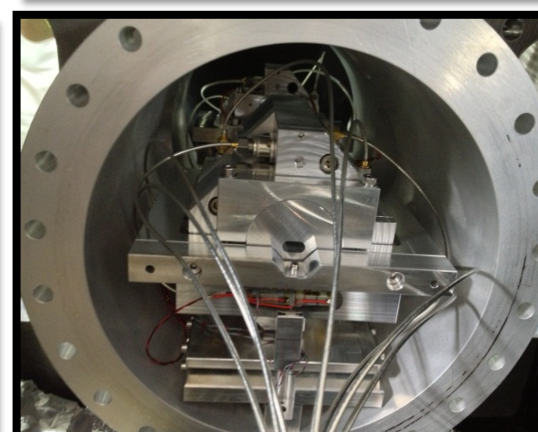
- **The IP-BPM system installation**



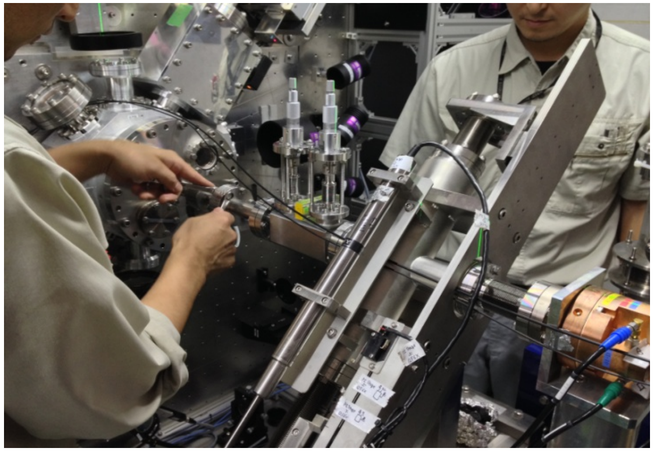




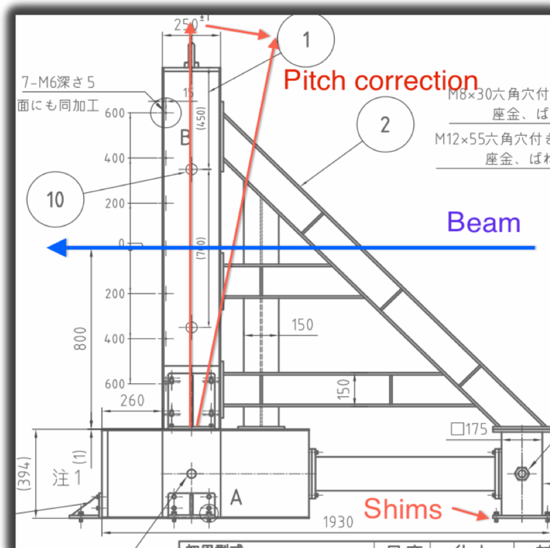




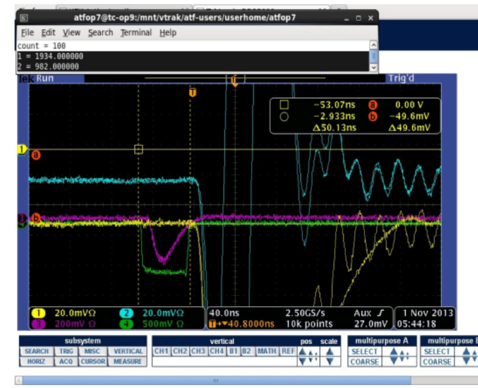
Installation of IP-BPM system



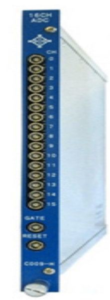
Ref. BPM install



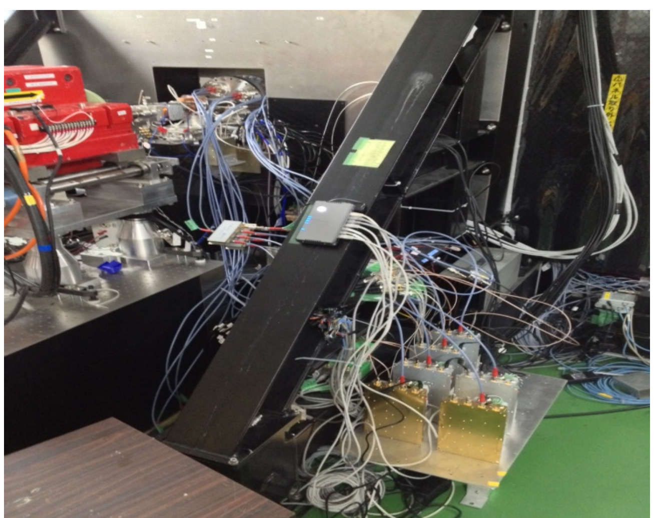
IP-chamber re-align
by using IP-BPMs

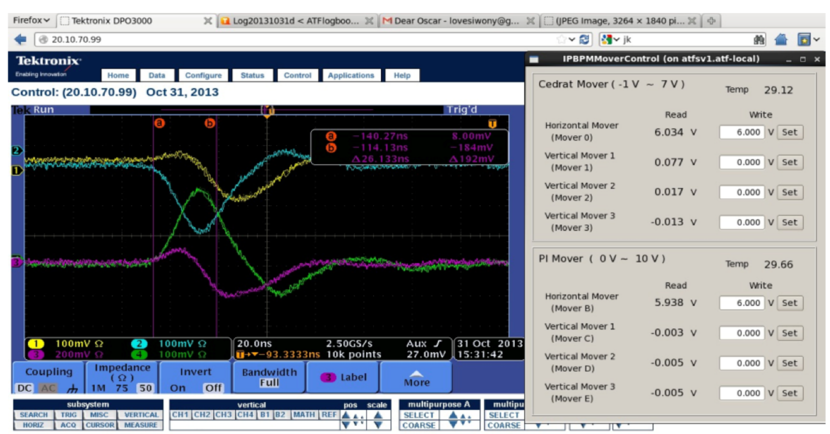


ADC system check
(C009-H)



Electronics w/ cable connection

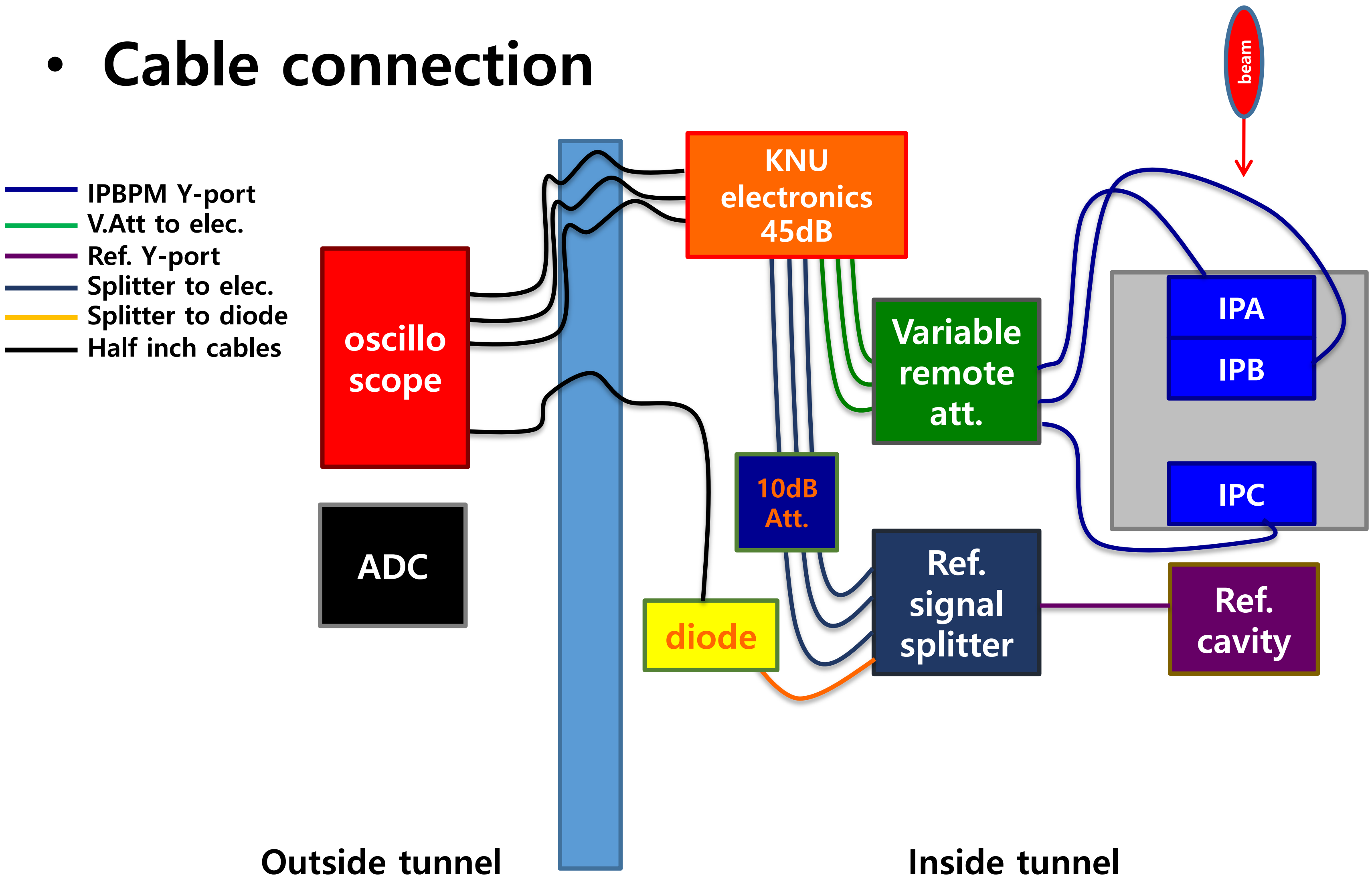




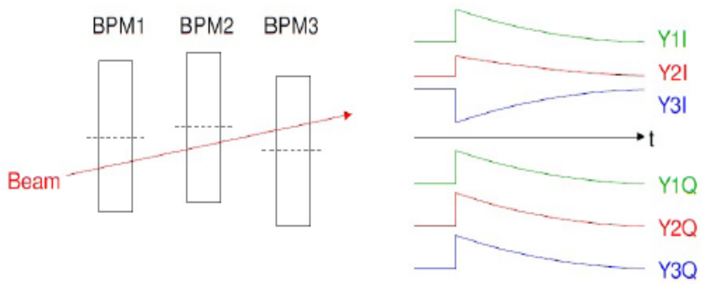
IP-mover
control
program
with
I-Q tuning

IP-BPM beam test
Experimental scheme

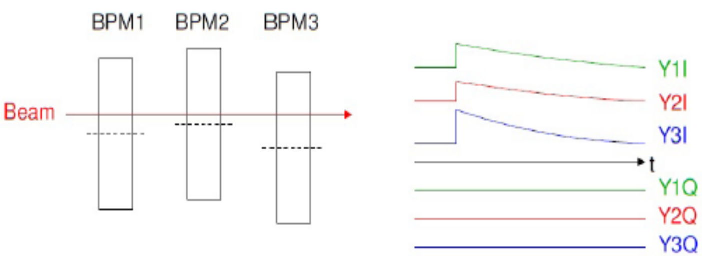
- Cable connection



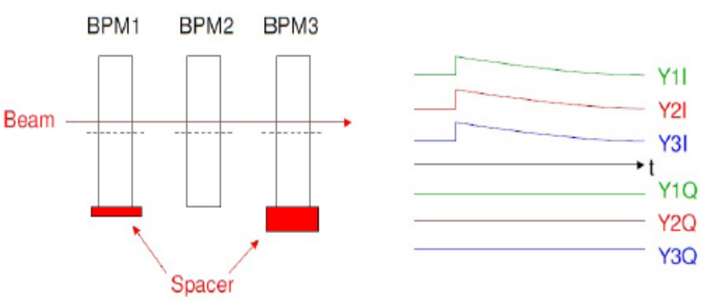
Bema position resolution measurements of Low-Q IP-BPM



(a) Before alignment



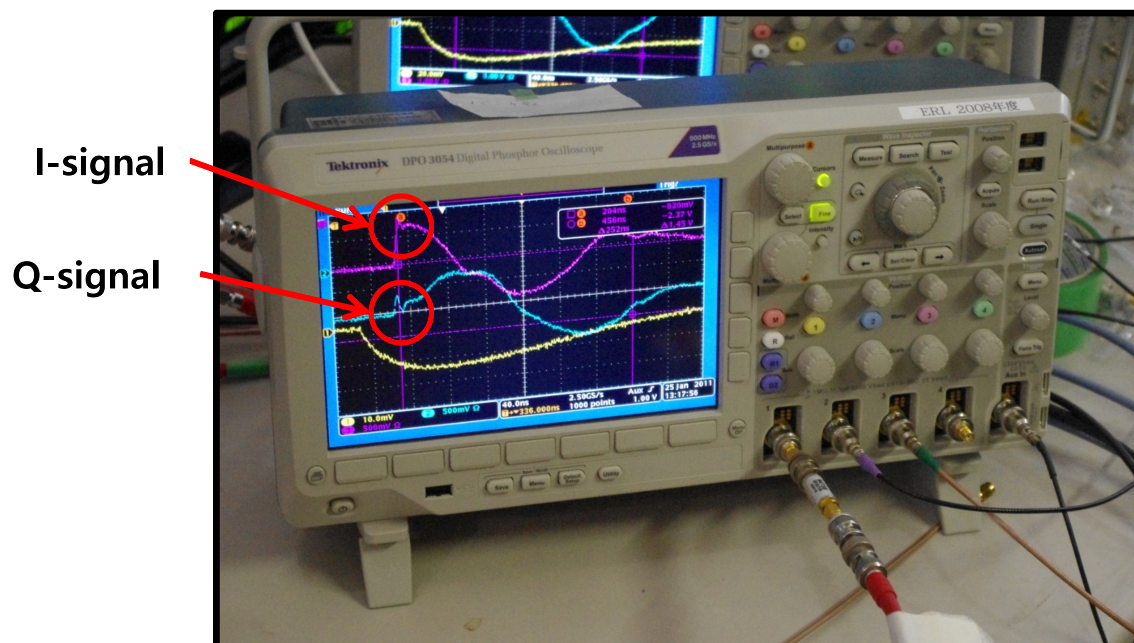
(b) Beam angle corrected



(c) Cavity height aligned

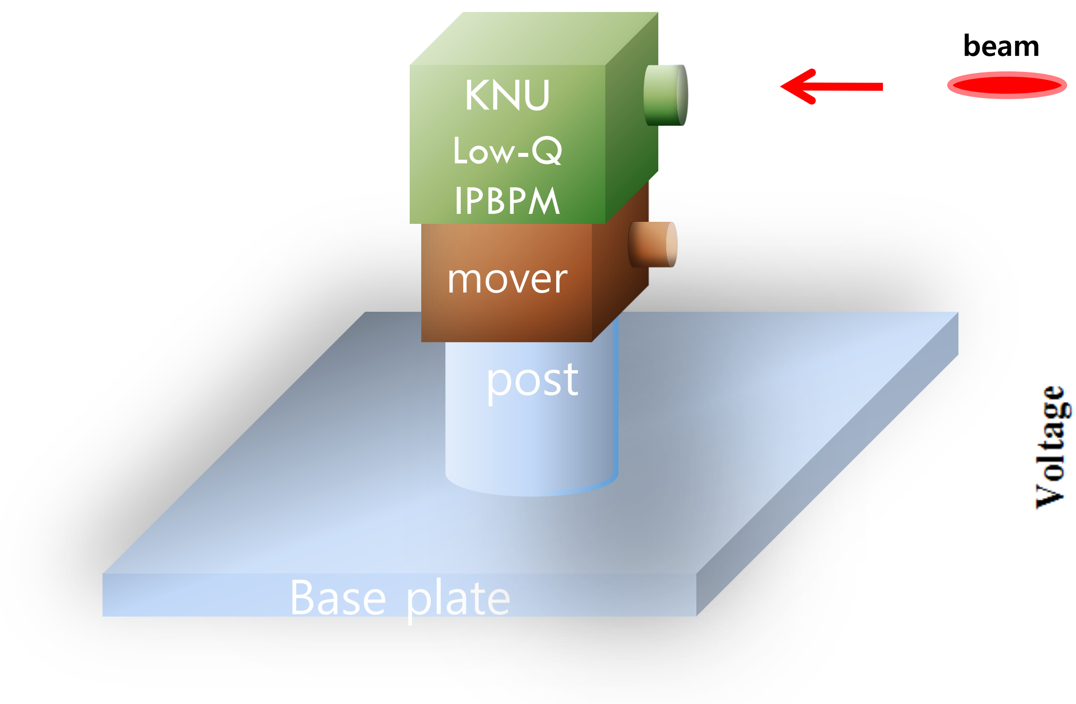
- **I-Q tuning**

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.



Bema position resolution measurements of Low-Q IP-BPM

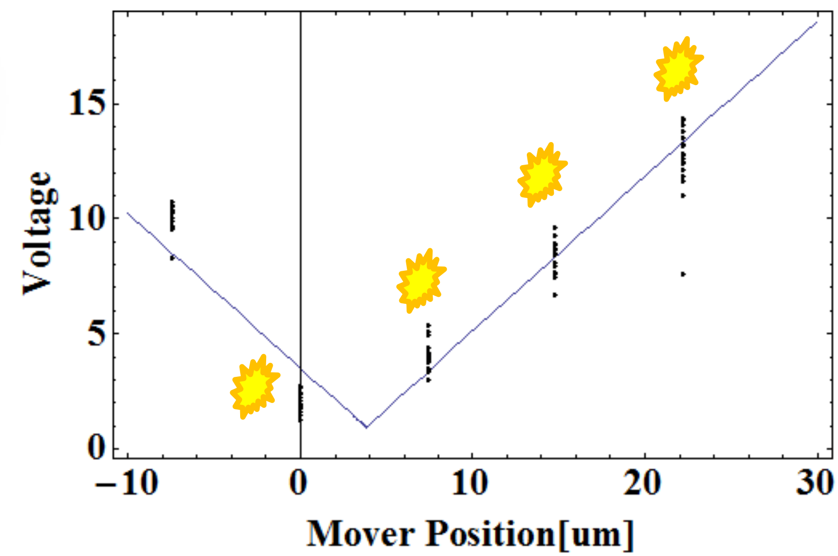
IP-BPM calibration beam test



IP-BPM

0.674 V/um

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



Calibration run of IPBPM

- We performed calibration run under the 0dB.
  - The used optics was 100 x 1000 beta optics, which optics has 1um level jitter.
  - The QDOFF was set to IP waist.
  - The data was taken at 150619 day shift.
  - The used method was integration method from #53 to #63 sample numbers.
  - Also I′ and Q′ does normalized by Ref_Y signal with same sample points region.

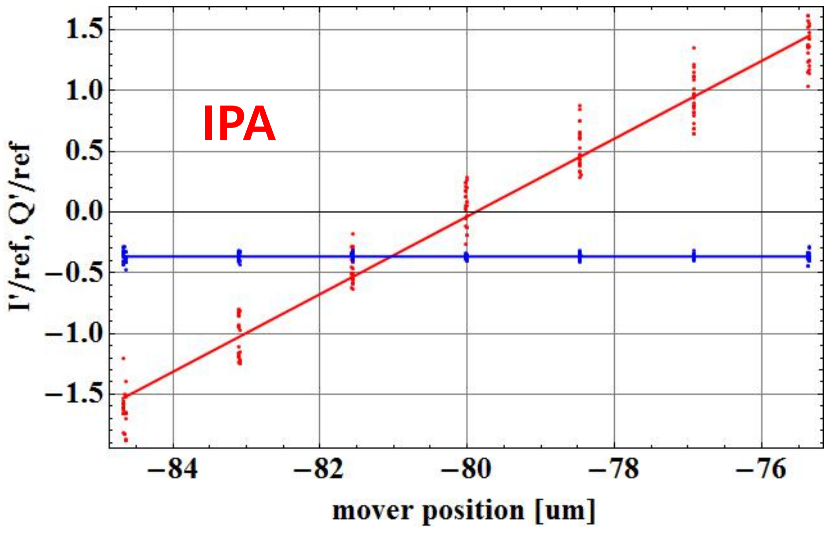
- The Calibration factor was calculated by (All the signal was integrated),

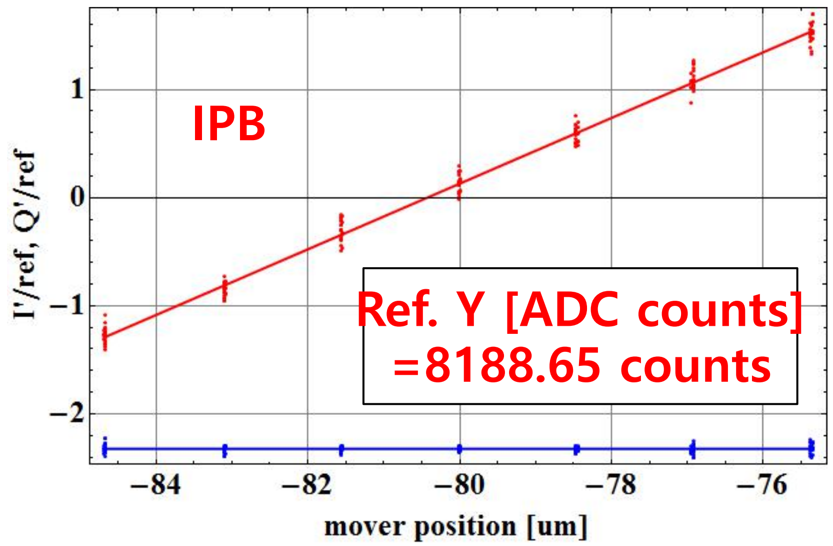
  I′ = (I*CosX + Q*SinX) [counts], Q′ = (Q*CosX - I*SinX) [counts]

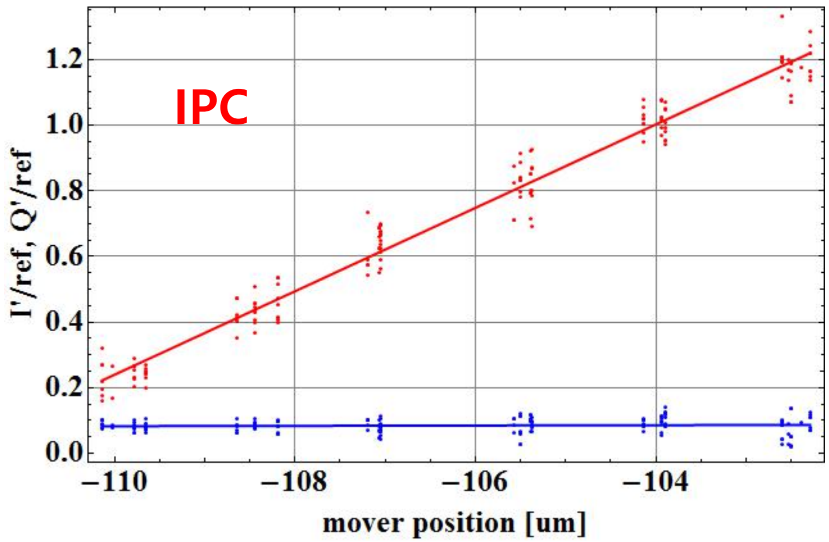
  Calibration factor = (Δ I′ [coounts])/(Δ Mover position [um])

- All the I and Q signal was not performed a mean subtract calculation.
  Because we installed C-band region band pass filters.

Calibration test by using Low-Q IP-BPM







Channel of BPM	Calibration factor [ADC counts/um]	Norm. Calibration factor [/um]
IPA-YIQ	2618.96	0.3198
IPB-YIQ	2489.56	0.3040
IPC-YIQ	1040.60	0.1271

The method to calculate the residual of IP-BPMs

We take an extrapolating method by using geometrical relation between thr ee IP-BPMs.

Differences are expressed by ;

$$f_1 = I_1 - \frac{I_2 Z_{13} - I_3 Z_{12}}{Z_{23}} = \frac{I_1 Z_{23} - I_2 Z_{13} + I_3 Z_{12}}{Z_{23}}$$

$$f_2 = I_2 - \frac{I_3 Z_{12} + I_1 Z_{23}}{Z_{13}} = \frac{-I_1 Z_{23} + I_2 Z_{13} - I_3 Z_{12}}{Z_{13}}$$

$$f_3 = I_3 - \frac{I_2 Z_{13} - I_1 Z_{23}}{Z_{12}} = \frac{I_1 Z_{23} - I_2 Z_{13} + I_3 Z_{12}}{Z_{12}}$$

$$f_0 \equiv I_1 Z_{23} - I_2 Z_{13} + I_3 Z_{12}$$

$$f_1 = \frac{f_0}{Z_{23}}, \quad f_2 = \frac{f_0}{Z_{13}}, \quad f_3 = \frac{f_0}{Z_{12}}$$

$$\frac{\partial f_0}{\partial I_1} = Z_{23}, \quad \frac{\partial f_0}{\partial I_2} = -Z_{13}, \quad \frac{\partial f_0}{\partial I_3} = Z_{12}$$

Residuals are expressed by ;

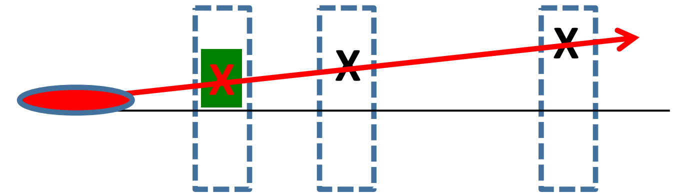
$$\begin{pmatrix} \Delta f_1^2 \\ \Delta f_2^2 \\ \Delta f_3^2 \end{pmatrix} = \begin{pmatrix} 1 & (\frac{Z_{13}}{Z_{23}})^2 & (\frac{Z_{12}}{Z_{23}})^2 \\ (\frac{Z_{23}}{Z_{13}})^2 & 1 & (\frac{Z_{12}}{Z_{13}})^2 \\ (\frac{Z_{23}}{Z_{12}})^2 & (\frac{Z_{13}}{Z_{12}})^2 & 1 \end{pmatrix} \begin{pmatrix} \sigma_1^2 \\ \sigma_2^2 \\ \sigma_3^2 \end{pmatrix} = A \begin{pmatrix} \sigma_1^2 \\ \sigma_2^2 \\ \sigma_3^2 \end{pmatrix}$$

Since det A is zero, $\sigma_1 = \sigma_2 = \sigma_3 \equiv \sigma$

$$\sigma = \Delta f_1 / \sqrt{1 + (\frac{Z_{13}}{Z_{23}})^2 + (\frac{Z_{12}}{Z_{23}})^2} = \Delta f_2 / \sqrt{(\frac{Z_{23}}{Z_{13}})^2 + 1 + (\frac{Z_{12}}{Z_{13}})^2} = \Delta f_3 / \sqrt{(\frac{Z_{23}}{Z_{12}})^2 + (\frac{Z_{13}}{Z_{12}})^2 + 1}$$

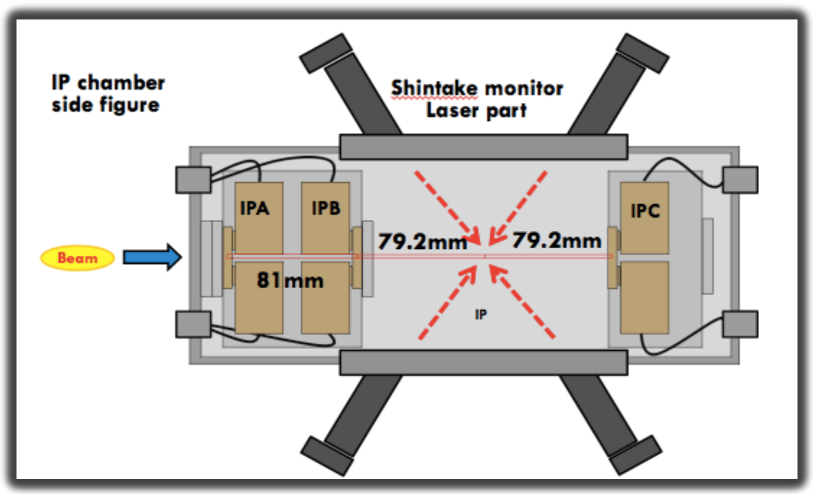
1

2013年 11月 8日 金曜日



Beam position measurement and prediction

	IPBPM-A (Interpolated by IPBPM-B and C)	IPBPM-B (Interpolated by IPBPM-A and C)	IPBPM-C (Interpolated by IPBPM-A and B)
Geometrical factor	0.531065	0.802629	0.271567



Resolution calculation: 0dB

- We performed resolution run under the 0dB
  - The used optics was 100 x 1000 beta optics, which optics has 1um level.
  - The QDOFF was set to IP waist.
  - The data was taken at 150619 day shift.
  - The used method was integration method from #53 to #63 sample numbers.
  - Also I' and Q' does normalized by Ref_Y signal with same sample points region.
  - The beam was set to few um offset position.

- The Calibration factor was calculated by (All the signal was integrated),

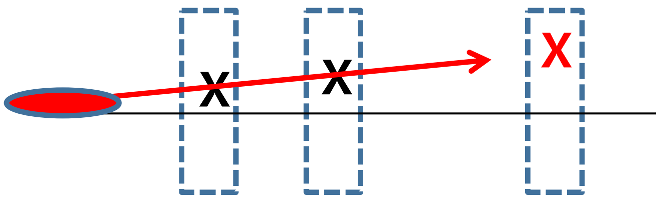
  I' = (I*CosX + Q*SinX) [counts], Q' = (Q*CosX - I*SinX) [counts]

  Calibration factor = (Δ I' [counts])/(Δ Mover position [um])

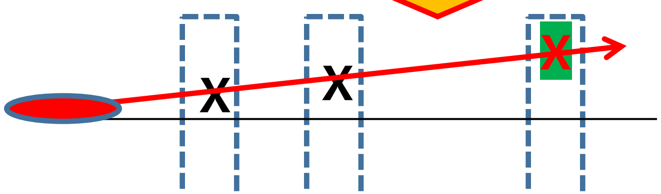
- All the I and Q signal was not performed a mean subtract calculation.

- Predicted position(ADC counts) for IPA was calculated as follow equation,
  - Predicted position of IPA-YI' = a1*IPB-YI'+ a2*IPB-YQ'+a3*IPC-YI'+ a4*IPC-YQ'+ a5*Ref-Y +a6*IPA-XI'+ a7*IPA-XQ' +a8*IPB-XI'+ a9*IPB-XQ'+a10*IPC-XI'+ a11*IPC-XQ'+ a12*Ref-X+a13
  - Residual of IPC-YI' = Measured IPC-YI' – Predicted IPC-YI'

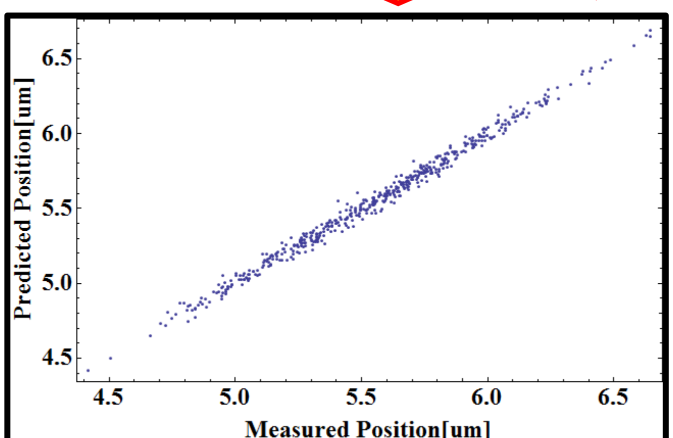
The results of IPBPM resolution test at June 2015 in ATF2



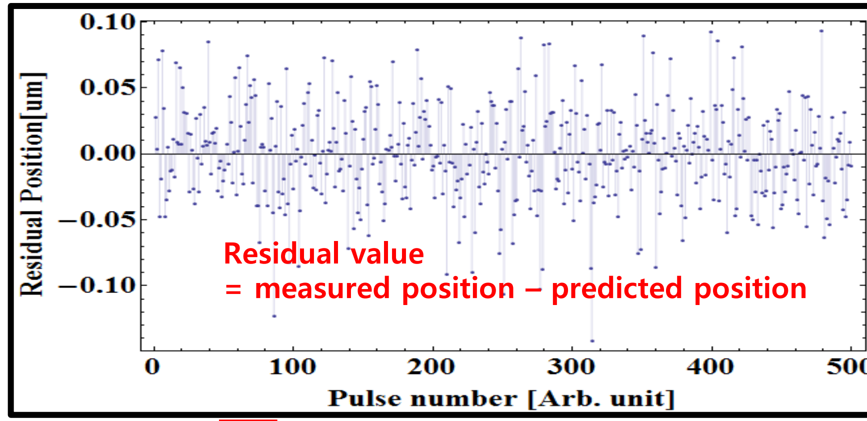
Beam position prediction

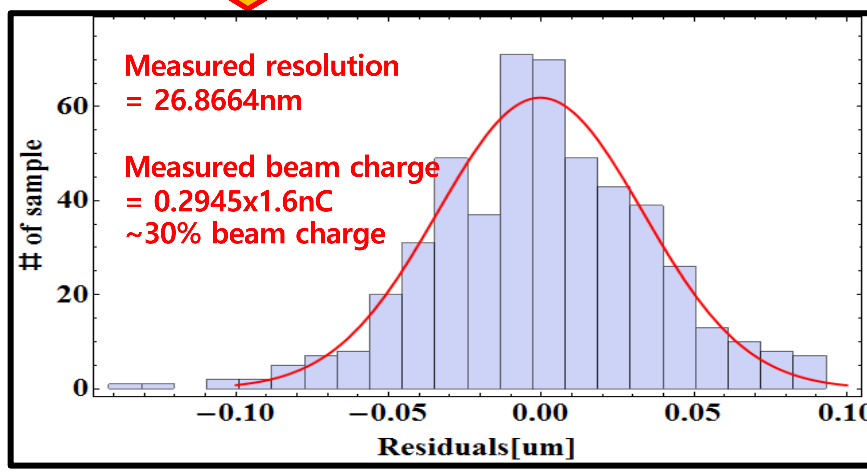


Beam position measurement



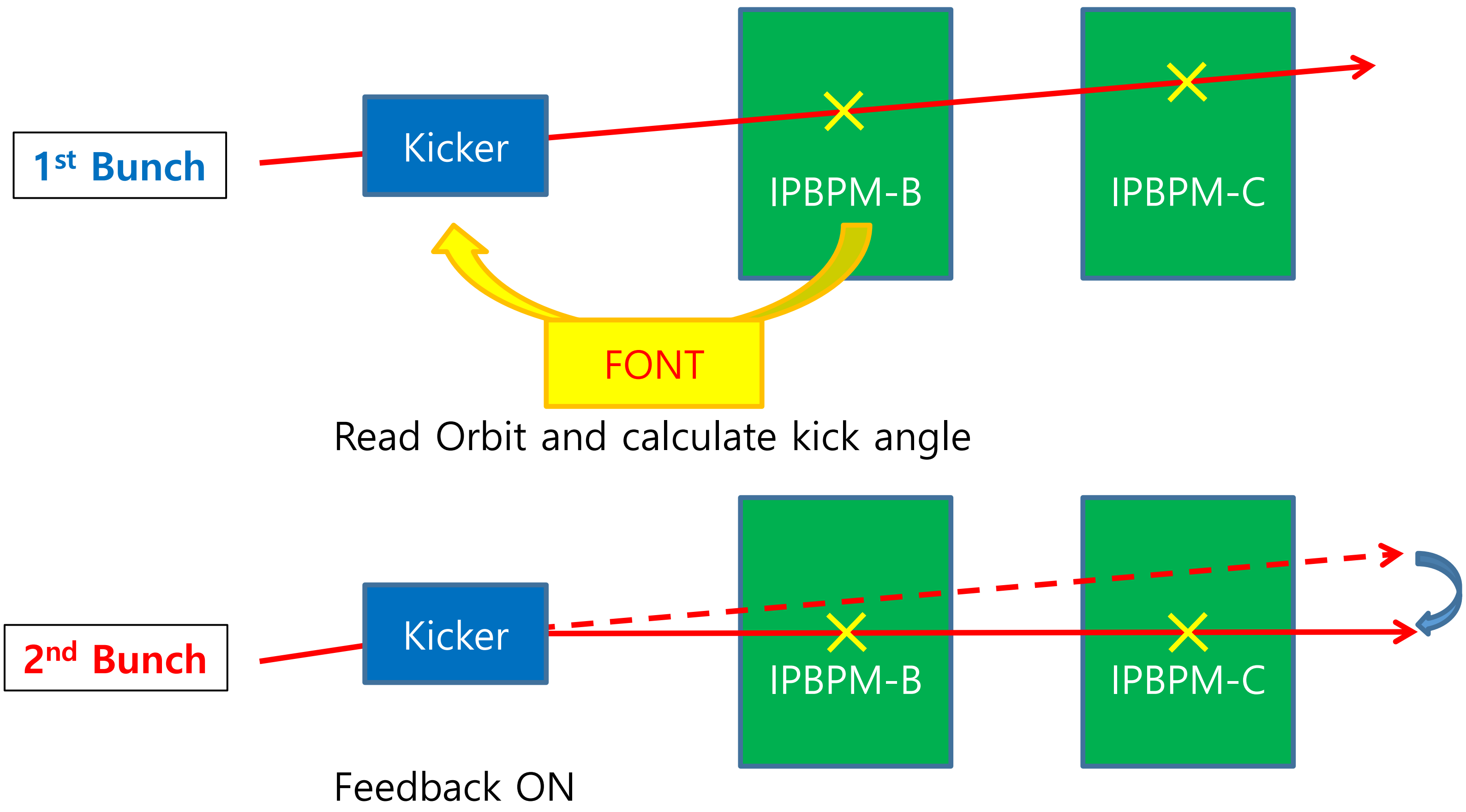
Convert to residual





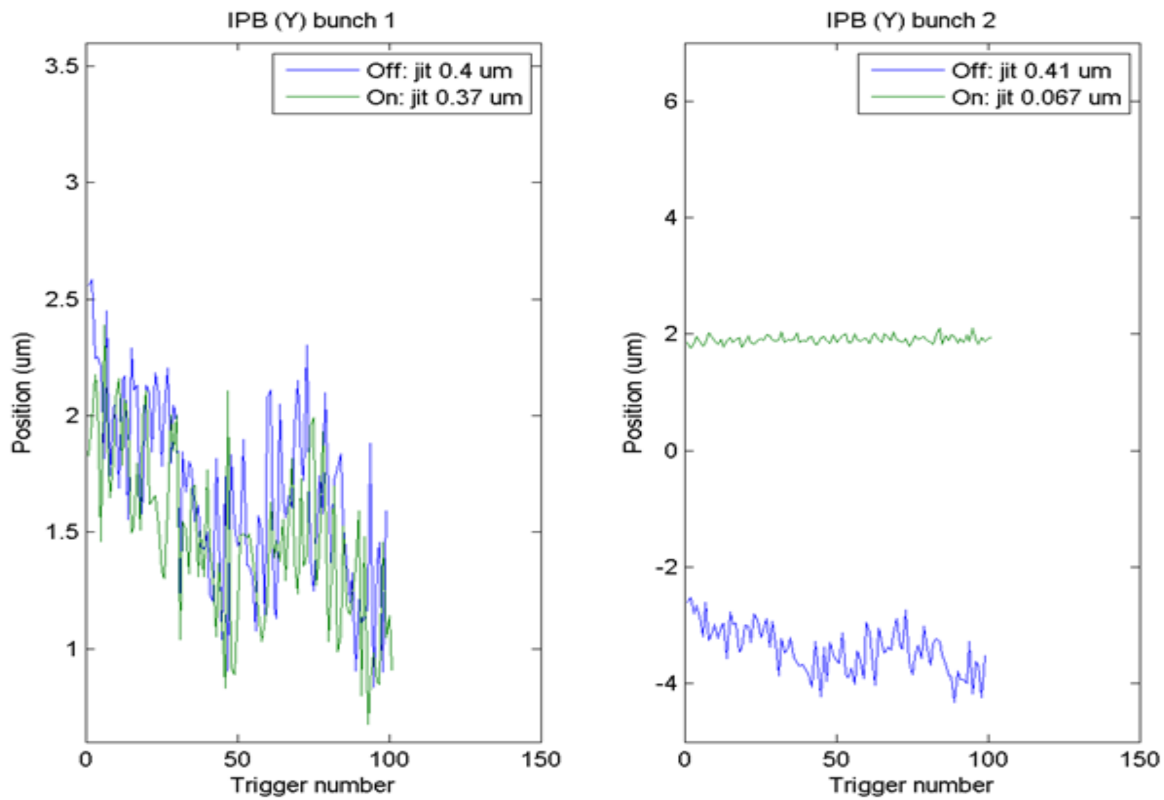
$$\text{Norm. Resolution} = \text{Geo. factor} \times \frac{\text{RMS of residual}}{\text{Calibration factor}} \times \frac{\text{Measured charge}}{\text{Nominal charge}} = \mathbf{7.9nm}$$

IPBPM orbit feedback study



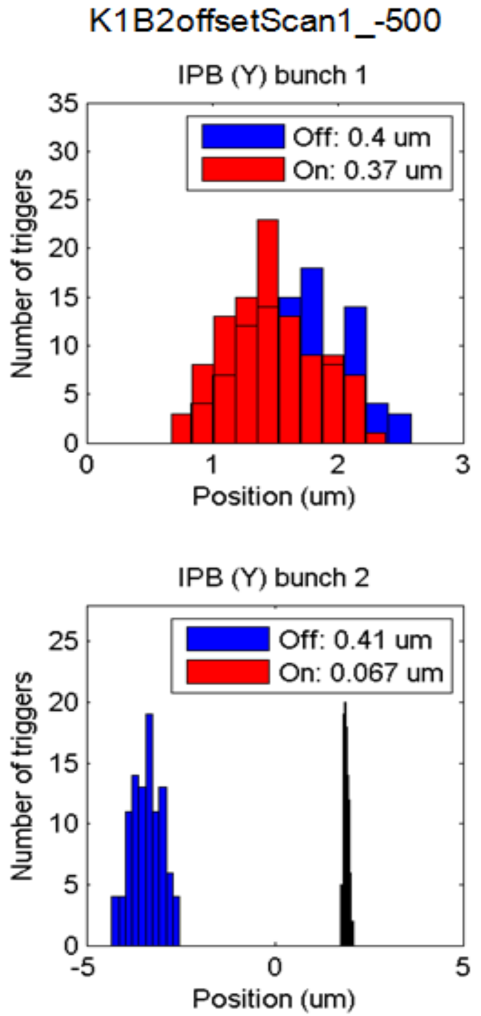
IPBPM orbit feedback study

Attenuation	QD0FF	Feedback	K1B2 offset
0 dB	137.4 A	On	-500



IPBPM orbit feedback study

Attenuation:	0 dB
AQF7FF(Y):	-950 um
QD0FF:	137.4 A
K1B2 offset:	-500 DAC
IP feedback:	On



Feedback off beam jitter: 370nm.
Feedback on beam jitter: 67nm
~82% beam jitter was reduced
And well focused orbit feedback.

KOREA UNIVERSITY

2022 가속기 및 빔 라인 미래인재
양성 교육단 여름학교

경청해 주셔서 감사합니다!

Thank you for your attention!