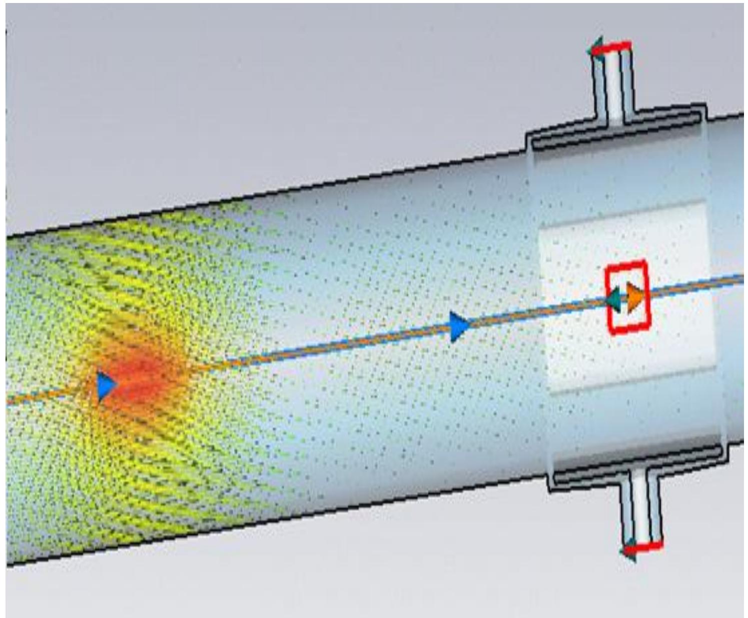
Tutorial on Electromagnetic Beam Position Monitors for Low-β high intensity linacs



4th *DITANET* Topical Workshop on High Intensity Proton Beam Diagnositics

Ivan Podadera, CIEMAT

27 September 2011

Input documents and references

Schools

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- P. Forck, DITANET School, 2011.
- P. Forck, Joint University Accelerator School, Archamps, France.
- K. Wittenburg, Hadron Machines Special Diagnostics, CAS School, Bilbao, 2011.

Reference articles

- Principle:
  - J. Bosser, *Beam instrumentation*, CERN-PE-ED-001-92
  - J. Cuperus, *Monitoring of particle beams at high frequencies*, CERN-PS-LIN-76-7, 1977.
  - R. E. Shafer, *Beam position monitor sensitivity for low-β beams*, AIP, 1994.
  - R. E. Shafer, *Beam position monitoring*, AIP 212, p. 26, 2009.
- Simulation:
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  - CARE Workshop, Lueneburg, 2006.
  - J. Tan et al., Beam Position Monitor System for the LINAC4, DIPAC 2011.
- Engineering:
  - M. Cohen-Solal, *Design, test and calibration of an electrostatic beam position monitor*, PRST 13, 032801 (2010).
  - G. Vismara, *Signal processing for beam position monitors*, AIP 546, p. 36, BIW 2000.
  - S.R. Smith, *Beam position monitor engineering*, AIP 390, p. 50, 2006.
- Operation:
  - D. Gilpatrick, *Experience with ground test accelerator beam measurement*

Outline

- Pickups for low-β beams
- Design workflow
- Electromagnetic design
- Manufacturing
- Electronics
- Test bench
- Overview

- **Pickups for low-β beams**
- Design workflow
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What are low-β BPMs?

Beam Position Monitors (BPM's) are beam diagnostics devices devoted to measure the transverse position of the center of charges of a particle beam.

Many devices and methods can be used for this. But what it is important is a reliable, robust and fast measurement during operation.

A electromagnetic pickup BPM is the best choice since they are:

- **Reliable:** simple mechanics and physics principle.
- **Robus**t since is **non-destructive** (does not intercept the beam).
- **Fast** (based on bunch frequency components).
- **Cheap**

Only AC current can be monitored => **Usage with bunched beams! (pulsed or CW)**

In high intensity hadron machines, low-β BPM's are used in the transport lines of the Linear Accelerator (LINAC), inside drift tubes or inside cryomodules.

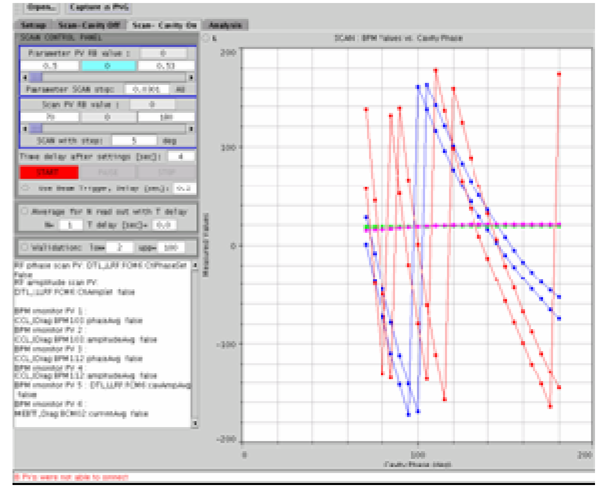
What do we use it for?

To detect dipole errors by measuring the position of the transverse beam centroid

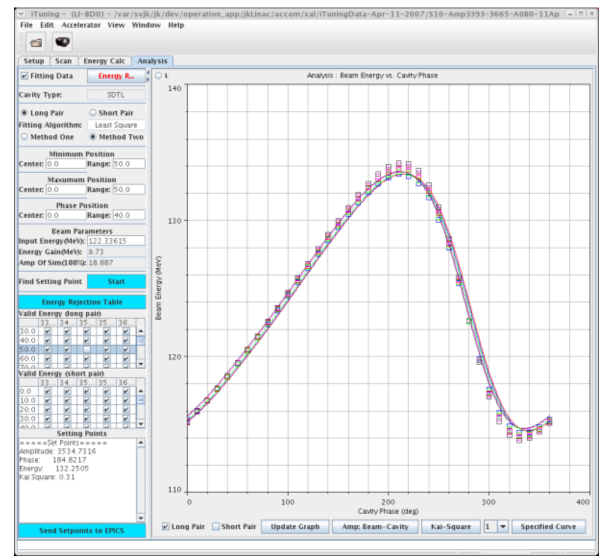
To measure the mean energy at the Diagnostics Plate

To tune the cavities with the beam phase

- *But also… Bunch length, "beam size",…*



SNS Pasta cavity tuning application



JPARC cavity tuning application

How does a BPM work?

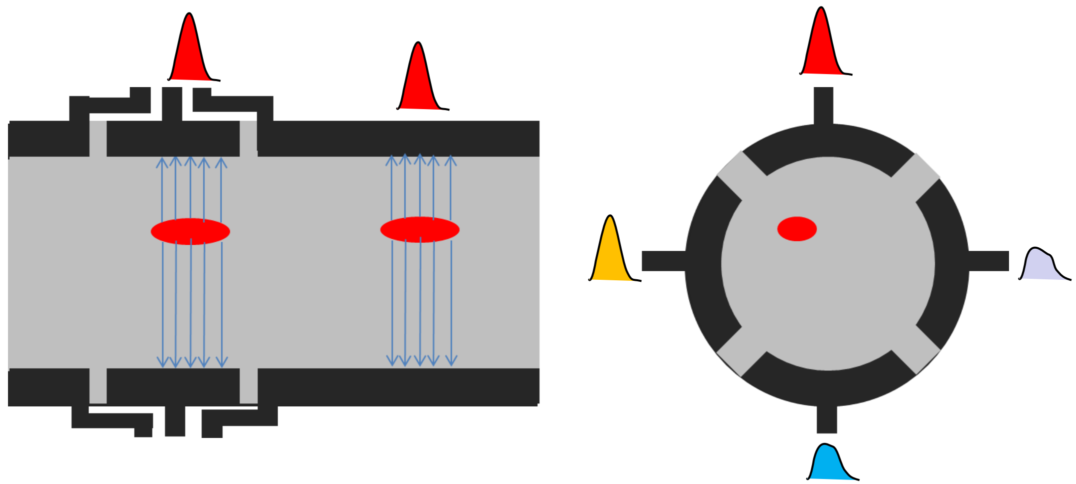
In RF LINACs beams are distributed in bunches of charged particles with a repetition rate equal to the RF period (normally between 50 – 500 MHz).

Each bunch has a special 3D distribution at each point of the accelerator.

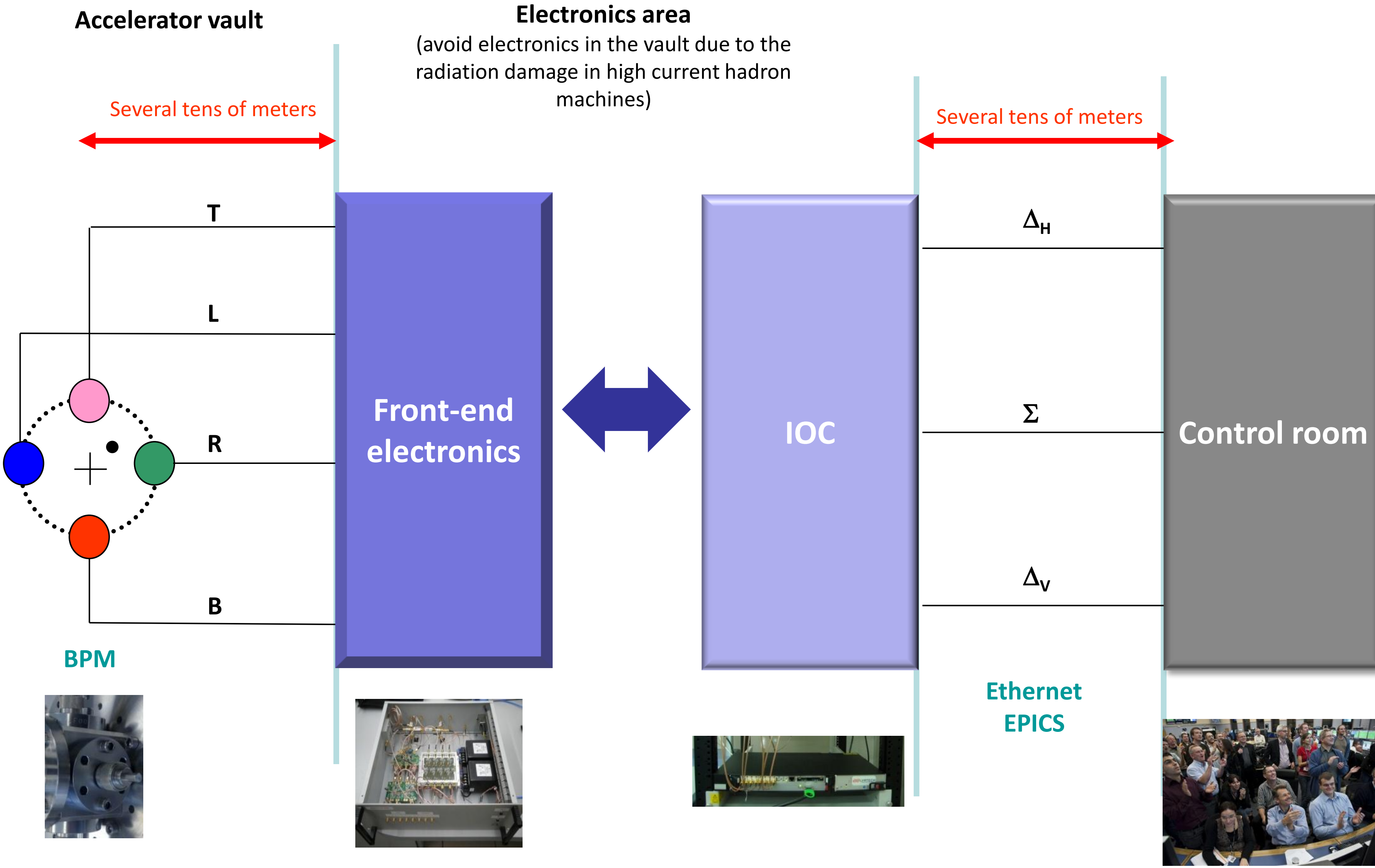
The combination gives a train of bunches with the subsequent frequency spectra.

In ultrarelativistic beams the longitudinal charge distribution of the high frequency part of the beam is reproduced exactly at the beam tube. The DC is then not observed.

Normally four electrodes/antennas/button/plates are placed axysymmetrically to detect the differential variations of the signal induced among each of them



What are the typical components?



Particularities of low-β beams

Current “densitiy” in A/m for.,..

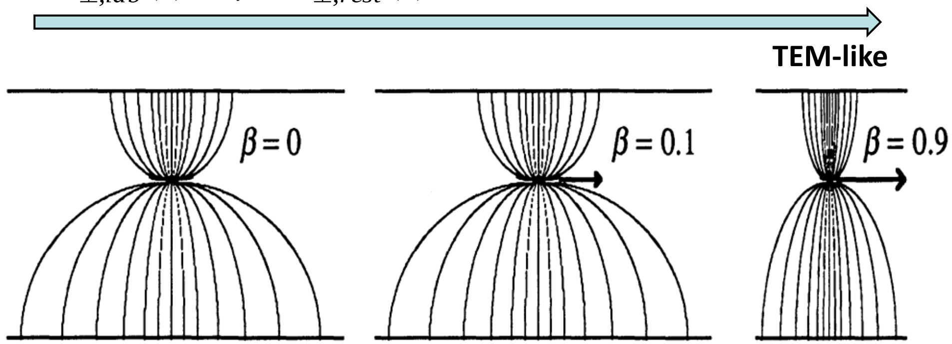
β=1

$$i_w(b,\alpha,t)=\frac{-I_b(t)}{2\pi b}\left[1+2\sum_{m=1}^{\infty}\left(\frac{r}{b}\right)^n\cos[m(\alpha-\theta)]\right]=\frac{-I_b(t)}{2\pi b}\left[\frac{b^2-r^2}{b^2+r^2-2br\cos(\alpha-\theta)}\right]$$

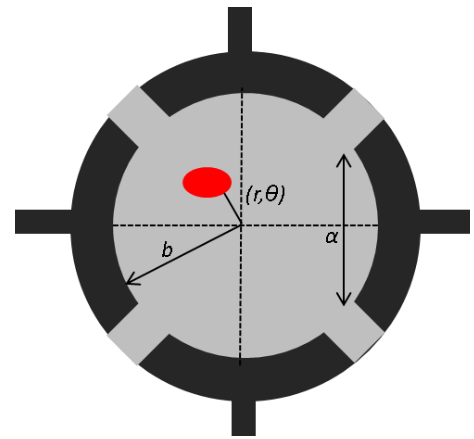
$$i_w(\omega,r,\alpha,\theta)=\frac{A_n\langle I_b\rangle}{\sqrt{2\pi b}}\left[1+2\sum_{m=1}^{\infty}\left(\frac{r}{b}\right)^n\cos[m(\alpha-\theta)]\right]$$

$$E_{\perp,lab}(t)=\gamma\cdot E_{\perp,rest}(t)$$

↑γ => ↓E



$$\sigma_t=\frac{b}{\sqrt{2\gamma\beta c}}$$



Any β

$$i_w(\omega,r,\alpha,\theta)=\frac{A_n\langle I_b\rangle}{\sqrt{2\pi b}}\left[\frac{I_0(gr)}{I_0(gb)}+2\sum_{m=1}^{\infty}\frac{I_m(gr)}{I_m(gb)}\cos[m(\alpha-\theta)]\right]$$

$$g(\omega)=\frac{\omega}{\beta\gamma c}$$

Equivalent expressions for $g\sim0$

Space charge and diffuse beams

High current are dominated by the space charge of the beams. Obviously, high current beams are bigger than low current ones, tending to more diffuse beams.

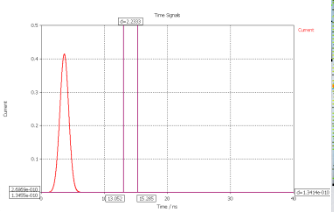
According to the approximations given in ***Comparison of beam-position transfer functions using circular beam-position monitors*** **(Gilpatrick, PAC97),** the sensitivity change can be noticed if the sum of the beam rms transverse width σ and the beam offset $(\bar{x}, \bar{y})$ is greater than 65% of the electrode radius b.

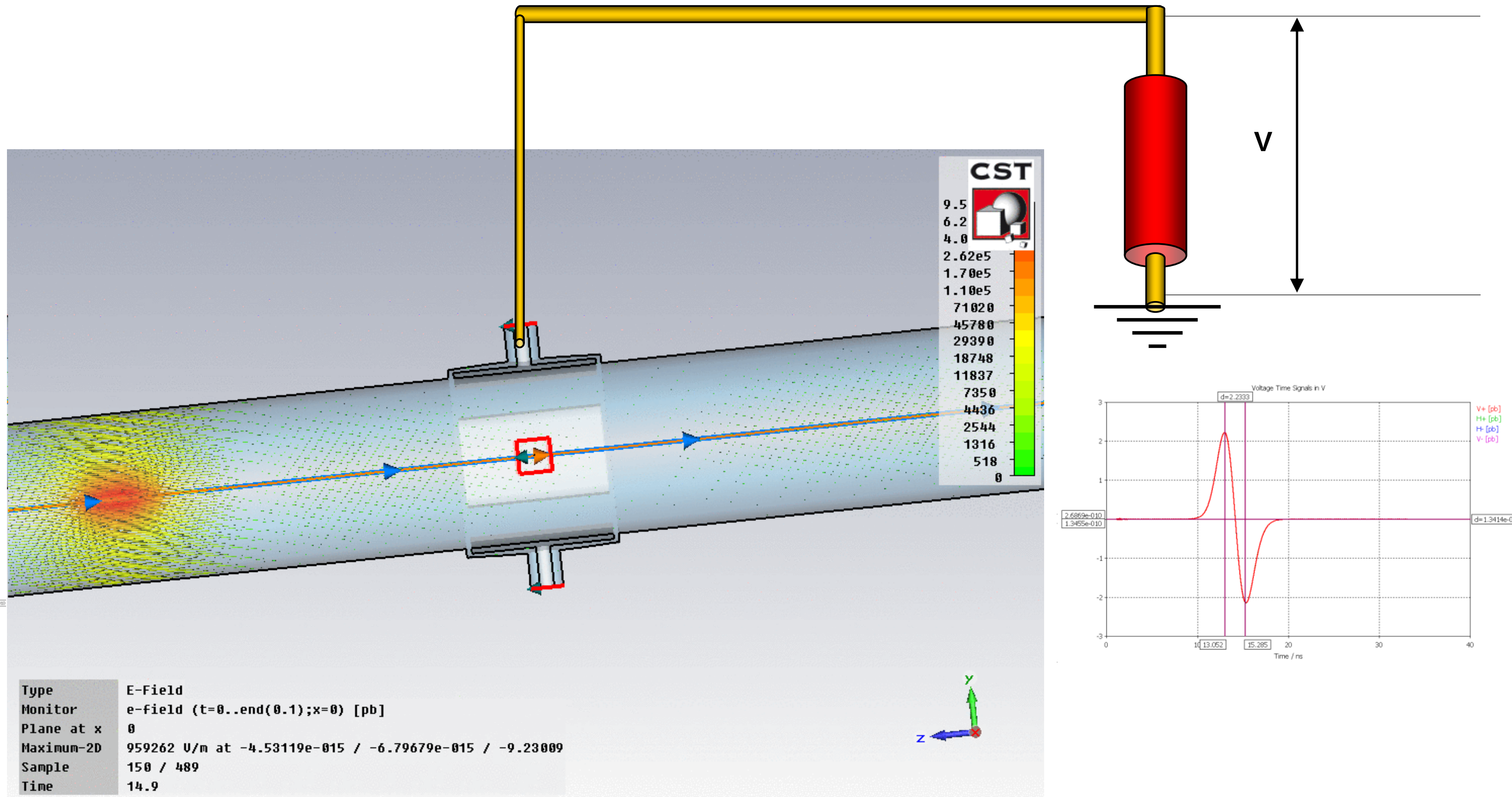
For example, for a BPM of 150 mm aperture that means the rms width should be greater than 50 mm for this effect to be noticeable. For a 10 mm beam radius, the maximum offset that can accepted is then 40 mm

Total image current in an electrode created by a diffuse beam

$$I_T = \sum_{n=-3\sigma}^{+3\sigma} \sum_{m=-3\sigma}^{+3\sigma} \hat{I}_T a_n b_m e^{\frac{-(x_n^2 - \bar{x}^2)}{2\sigma^2}} e^{\frac{-(y_n^2 - \bar{y}^2)}{2\sigma^2}}$$

Simulation of low-β BPMs



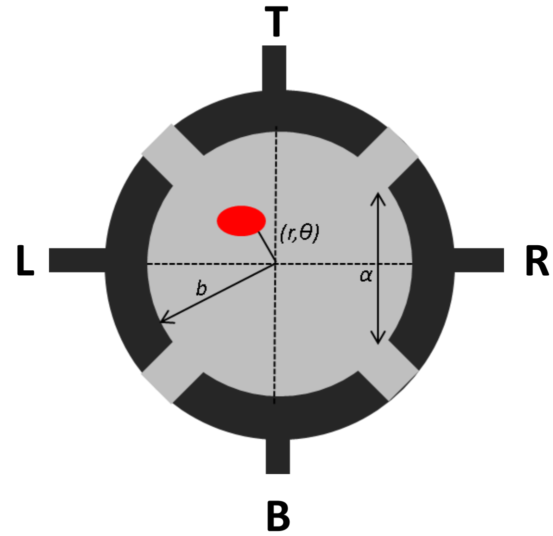


5 MeV, d+
β = 0.0727

Position and phase measurement

Transverse position

- **Differential measurement** of the image current created by the beam on opposite electrodes.
- As the signal strength in each electrode is current dependent, the differential measurement has to be normalized by the total signal (sum signal, *Σ*) or at least by the total signal strength of the pair of electrodes.
- The relation between the real beam position and the transfer function is the **sensitivity *S***. In the center region, the sensitivity (or the inverse ***k***) is constant and is defined as typical parameter of each pickup.
- Delta over sum or log transfer function are the preferred choices.



Phase

- **Relative measurement** of the phase of the bunches (at a certain frequency harmonic) with respect to the RF of each cavity, or an absolute measurement with respect to a general RF reference.
- The phase should be calculated using the sum signal of the current of all the electrodes.

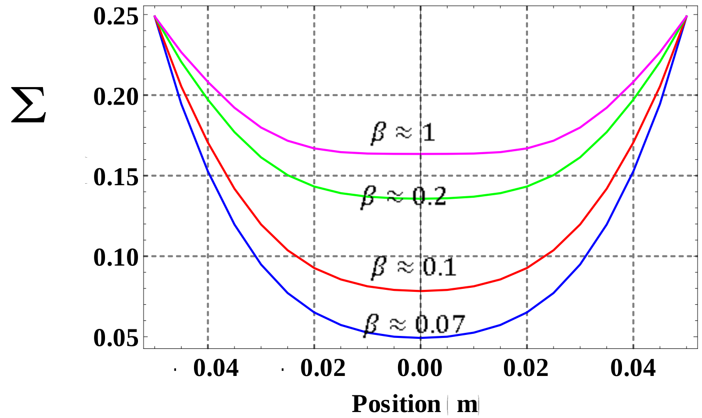
More used transfer functions

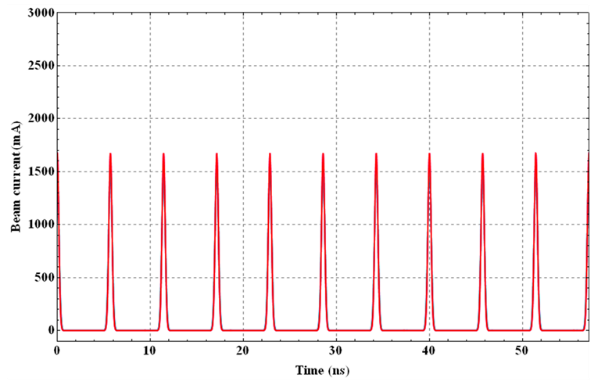
Delta over sum (DOS or Δ/Σ)	$\Delta_x/_{\Sigma} = \frac{R-L}{R+L+T+B}$ $\Delta_x/_{\Sigma'} = \frac{R-L}{R+L}$	$x = \frac{1}{S_x}\frac{\Delta_x}{\Sigma} + \delta_x =$ $= k_x \frac{\Delta_x}{\Sigma} + \delta_x =$
Log-ratio	$\left(R/L\right)_{dB} = 20\log\left(R/L\right)$	$x = \frac{1}{S_{x-dB}}\left(R/L\right)_{dB} + \delta_{x-dB}$

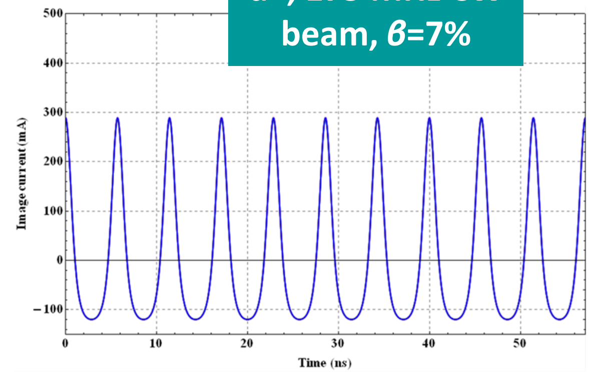
Position measurement with low-β beams

Sensitivity of the BPM **depends on the beam energy, the measurement frequency and the beam position *S(β,f,r)***.

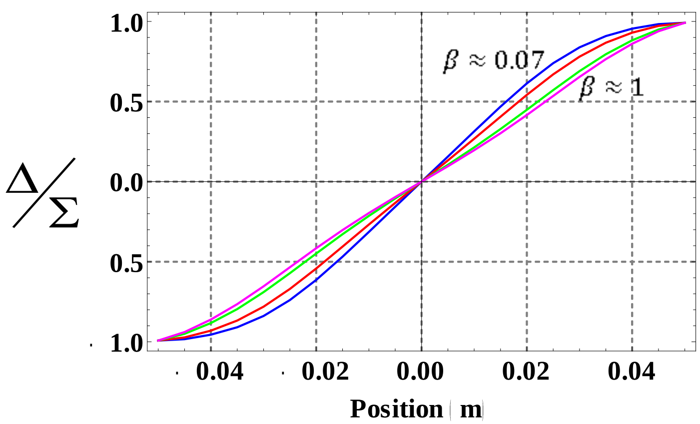
Unlike the signal level, in principle it is not dependent on the bunch length.

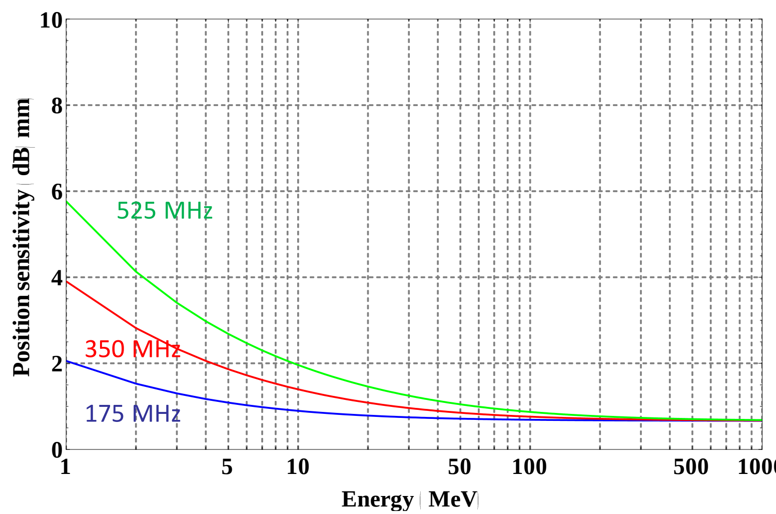






d+, 175 MHz CW beam, *β*=7%





Mean energy measurement

Three BPM's for the TOF measurement (two of them very close for N pre-determination)

Striplines seems to have a better phase accuracy (Σ) than buttons*

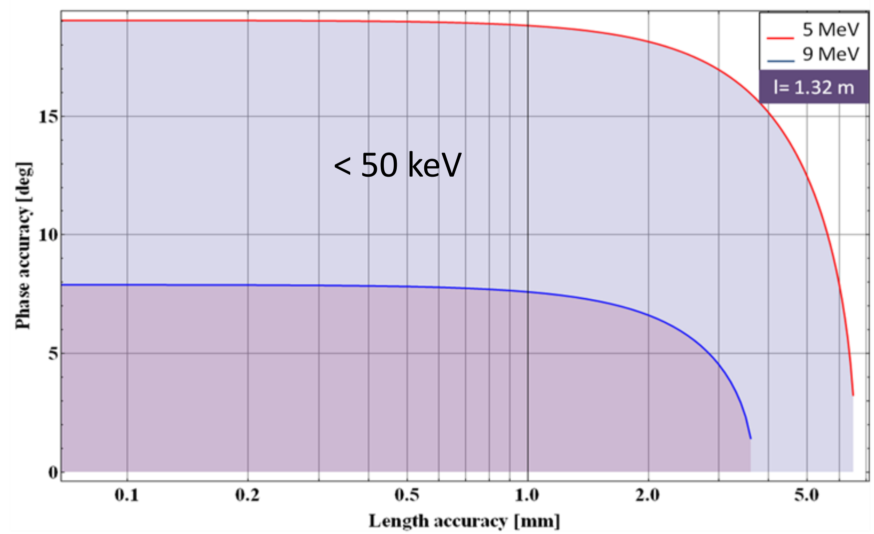
Good alignment and distance measurement of three BPM's is required.

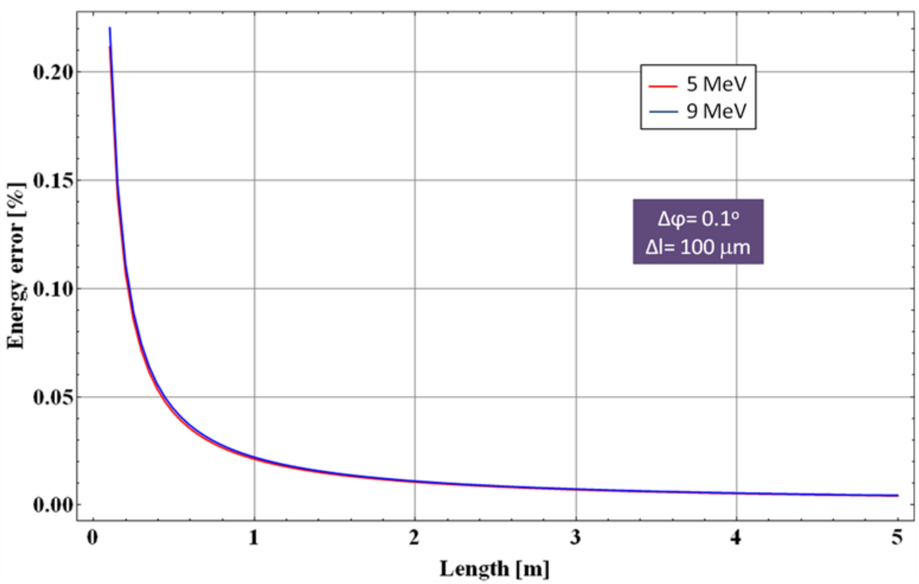
$$\frac{\Delta\beta}{\beta} = \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{NT + t}\right)^2}$$

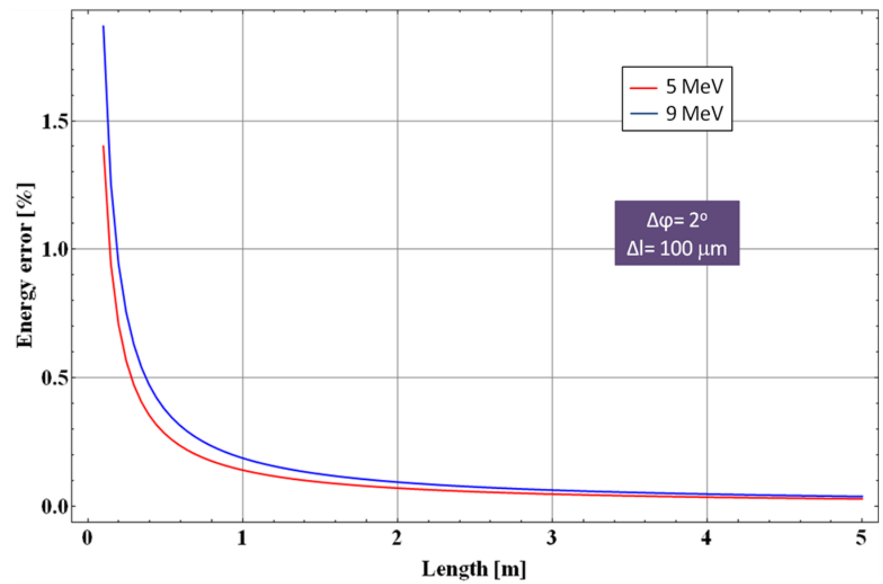
t can be as wellthe phase

Low energies:

$$\frac{\Delta T}{T} \approx 2\frac{\Delta\beta}{\beta}$$







~2 keV @ 5/9 MeV

~20 keV @ 5/9 MeV

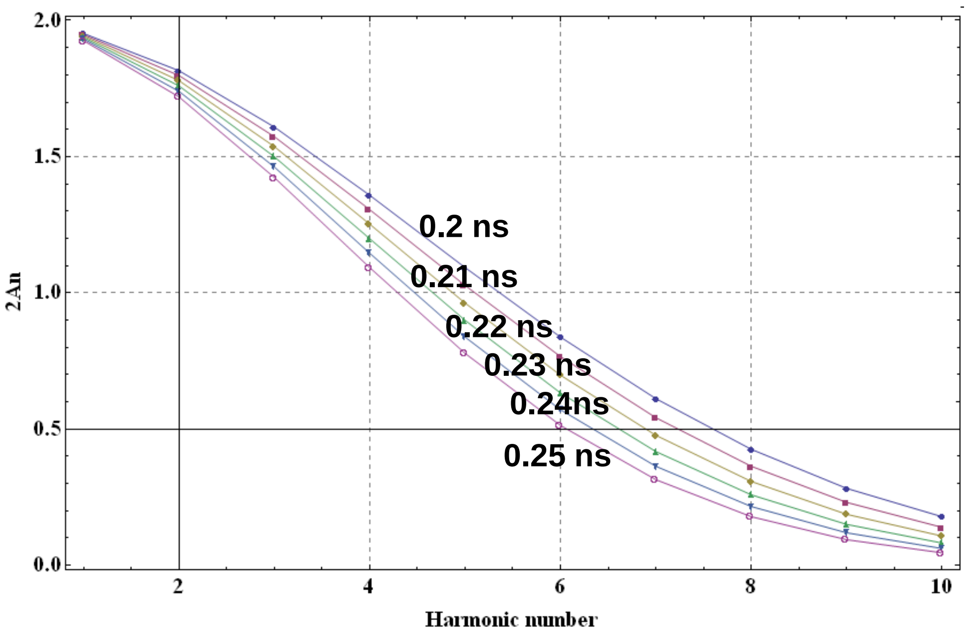
S. Kurennoy, Beam position monitors for SNS LINAC

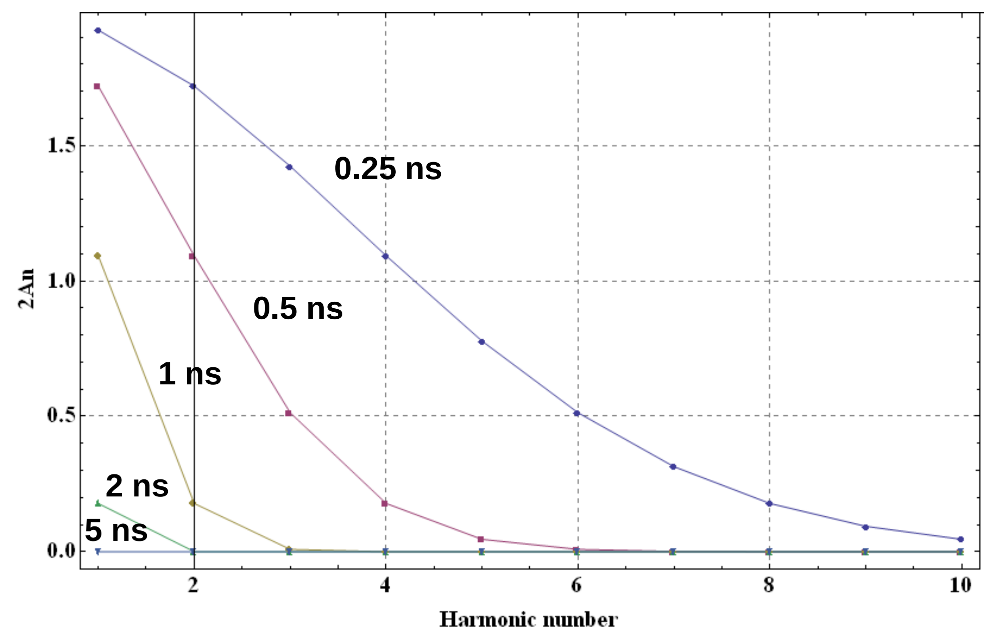
Bunch length measurement*

*C. Deibele, Beam Instrumentations for High Power SNS operation, presentation at CERN, 2008

- Frequency harmonics are bunch shape dependent $A_n(\omega)$
- Technique valid only if <*I*> and beam position is constant.
- More sensitive for higher frequency harmonics *n*>1

$$U_b(\omega) \propto A_n \langle I \rangle \Longrightarrow A_n = e^{-\frac{(2\pi n \sigma f_0)^2}{2}}$$ **(gaussian)**





- Pickups for low-β beams
- **Design workflow**
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Resolution and accuracy

Resolution

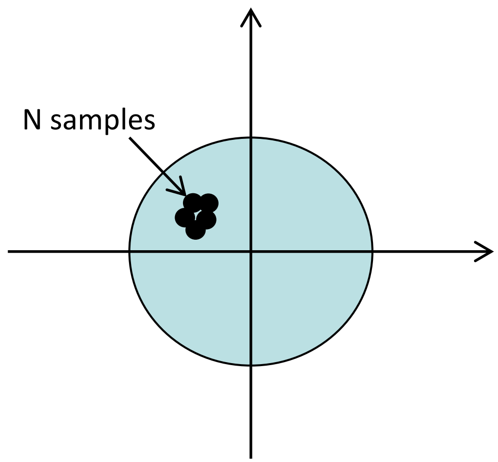
- the minimum beam displacement resolvable.
- It depends mainly on the signal to noise ratio (thermal noise…)
- It is function on the beam current (electrode signal), the bandwidth of the measurement, the position*…
- The measurement can be averaged with the number of samples *N*:

$$\sigma_{av} = \frac{\sigma}{\sqrt{N}}$$

**M. Cohen, 10.1103/PhysRevSTAB.13.032801*

Accuracy

- Error of the measurement with respect to the defined accelerator axis
- It is a chain of many independent errors: alignment of BPM, manufacturing, electrical offset, resolution…
- It is the one normally used by the beam dynamics codes.



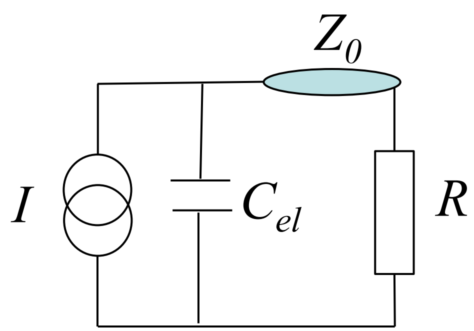
Capacitive and stripline

$$U(\omega) = Z_t(\omega) I_b(\omega)$$

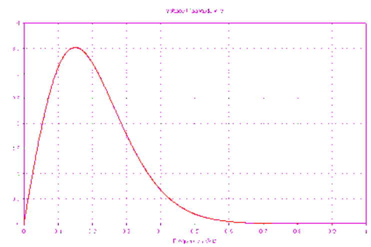
Electrode signal — $U(\omega)$

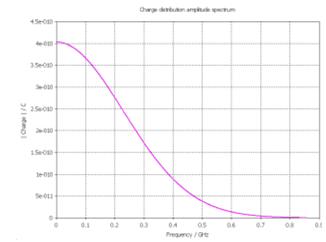
Transfer impedance — $Z_t(\omega)$

Beam current (excitation) — $I_b(\omega)$

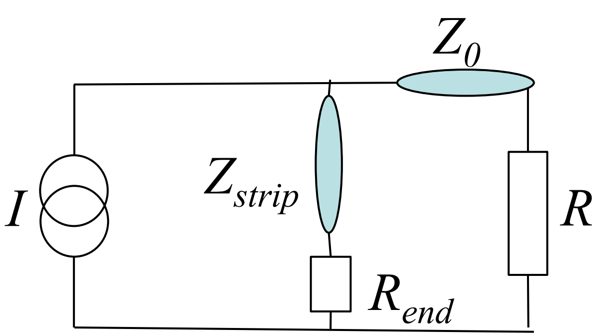


Capacitive BPM model



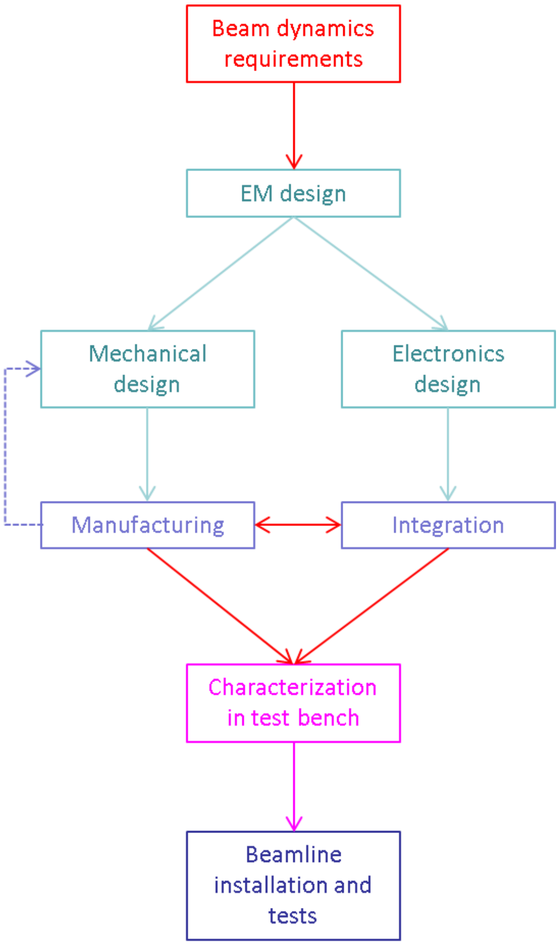


Capacitive	Stripline (normally shorted R_{end}=0)
$Z_t = \frac{1}{\beta c}\frac{1}{C_{el}}\frac{A}{\pi b}\frac{i\omega RC}{1+i\omega RC}$	$Z_t = Z_{strip}\frac{\alpha}{2\pi}\sin\left[\frac{\omega l}{2c}\left(1/\beta_s + 1/\beta_b\right)\right]e^{i\left(\pi/2 - \omega l/c\right)}$
High pass filter with $f_c = \frac{1}{2\pi RC}$	Maximum response for a given frequency at $L_{opt} = \frac{\lambda}{2}\left(1/\beta_s + 1/\beta_b\right)^{-1}$

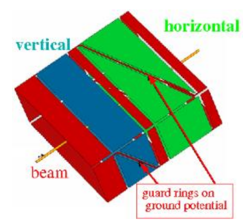


Stripline simplified model

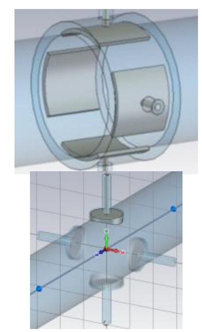
Design process

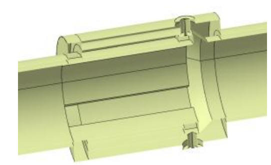


	Shoe-box (linear capacitive)	Capacitive/Button	(micro)Stripline
Linearity	Good	Fair/Poor	Fair
Sensitivity	Good	Fair	Fair
Phase accuracy	-	Medium	Good
Space required	Big	Medium/ Small	Small
Spray particles sensitivity	High	Medium (50 Ω)	Low
Mechanical complexity	High	Medium/ Medium	Low
Reliability and maintenance	Bad	Bad/ Good	Medium



Picture from P. Forck



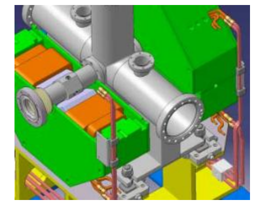


Low-β BPMs in present facilities

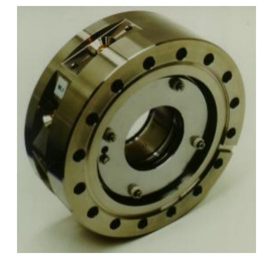
Beam properties	Facility							
	LEDA	**IPHI**	**SPIRAL 2**	**SARAF**	**UNILAC**	**LINAC4**	**SNS**	**J-PARC**
Particle	H^+	H^+	D^+	H^+/D^+	H^+	H^-	H^-	H^-
Main operation mode	CW	CW	CW	CW	PU	PU	PU	PU
Pulse/peak current (mA)	**100**	**100**	**5**	**2**	**70**	**40**	**36**	**30**
Maximum energy (MeV)	20	3	40	40	70	160	86.8	181
RF frequency (MHz)	350	352	88	176	352	352	402	324
Striplines/WCM	x					x	x	x
Capacitive/button pick-up		x	x	x	x			x
Capacitive ring (TOF)	x	x		x				

LEDA- microstripline

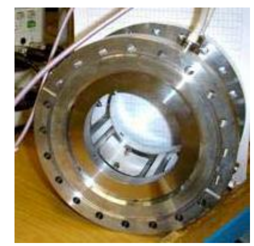
IPHI- capacitive



SPIRAL2- capacitive



UNILAC- capacitive



SARAF- stripline

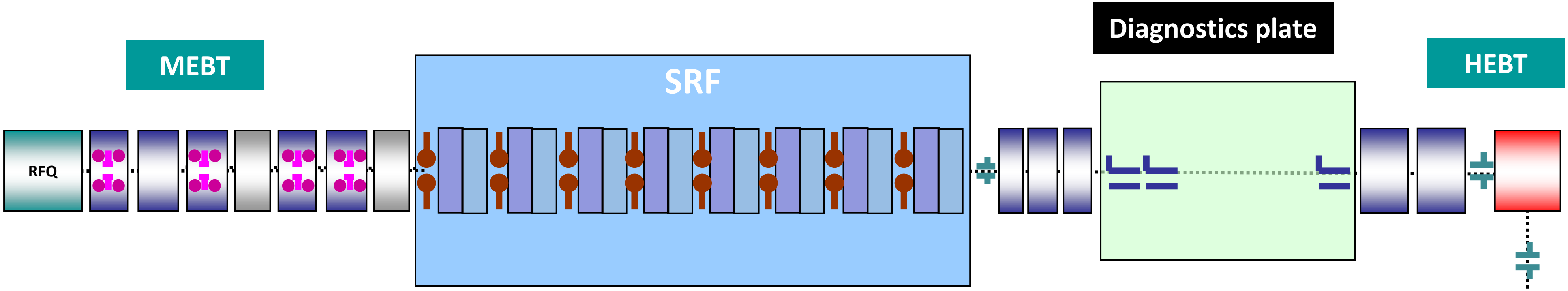
LINAC4- microstripline

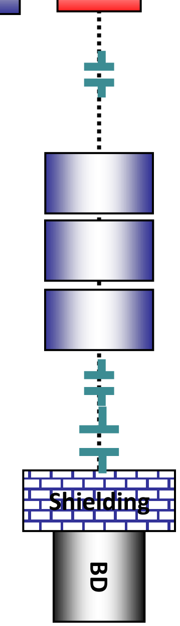
JPARC- stripline

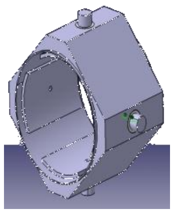
Typical requirements

- Position Accuracy: 1 % half-aperture (0.1-0.5 µm)
- Position Resolution: 0.1 % half-aperture (10-50 µm)
- Phase resolution: 1-3 deg
- Phase accuracy: 0.1-0.3 deg
- Current accuracy: 1 % of full current

Layout example: LIPAc

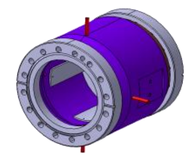




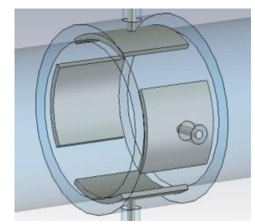


MBPM

CBPM



SBPM



HBPM

Region	BPM acronym	Aperture	Number	Symbol
MEBT	MBPM	48 mm	4	
SRF	CBPM	50 mm	8	
Diagnostics plate	SBPM	100 mm	3	
HEBT	HBPM	40/130/150 mm	1/2/2	
TOTAL			**20**	

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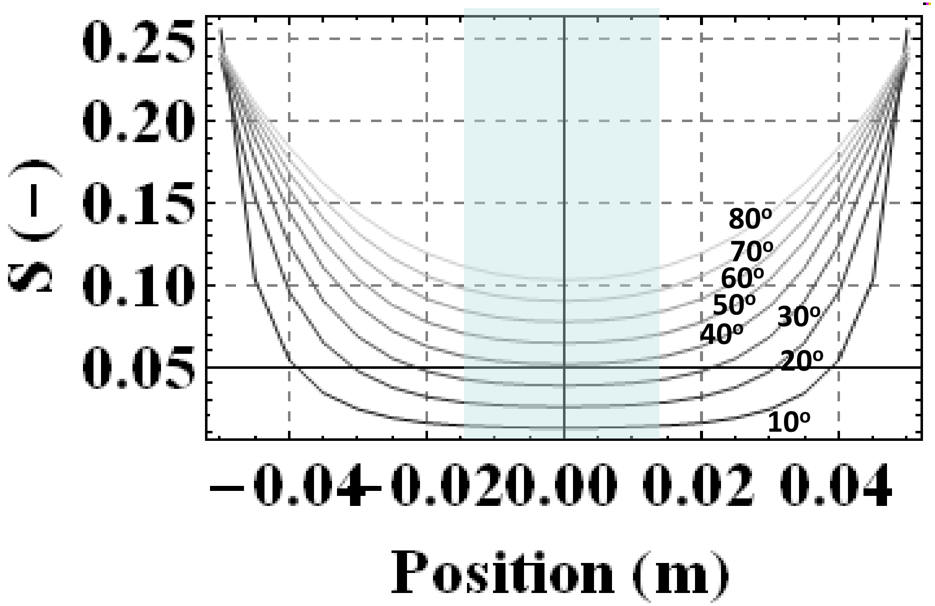
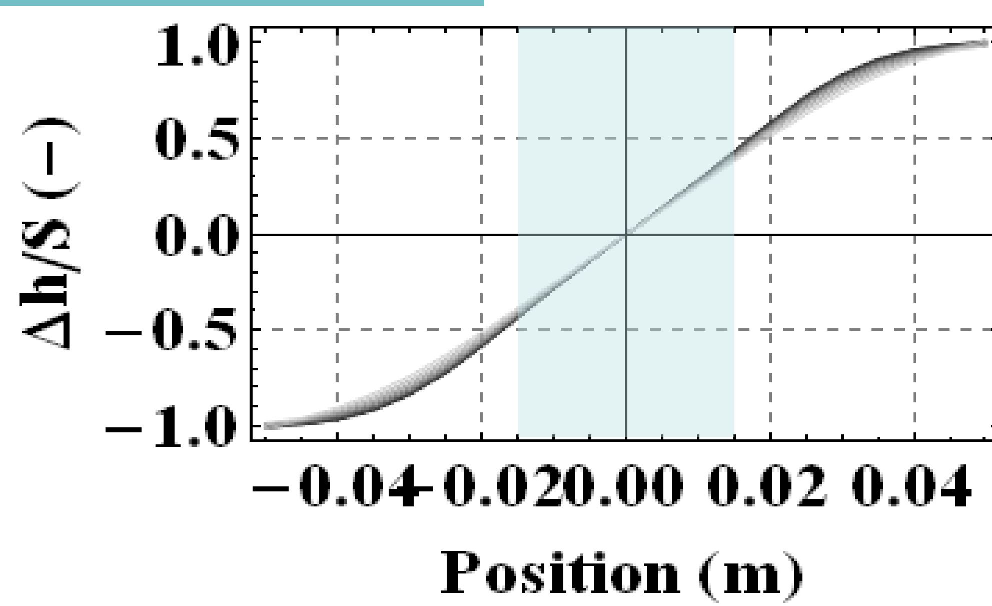
What to use to design a low-β BPM?

	3D HF Code (CST PS, Mafia, HFSS)	Electronics soft	Analytical
Optimization	Complex	Easy	Easy
Accuracy	Good	Fair	Low
Cost	Very high	Medium	"Low"
Comments	Good tool for verification of the theory model and checking of HF performances	Good tool to couple to electronics processing	Good tool for the start of the design

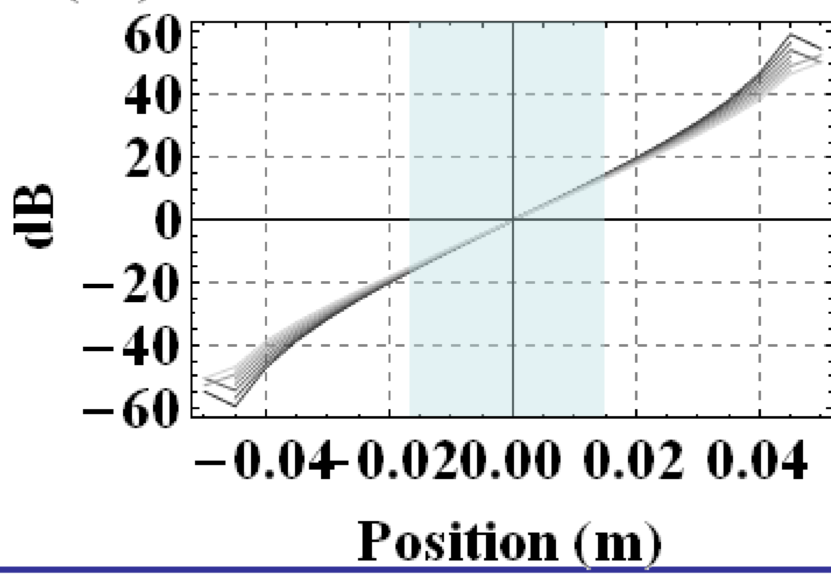
Analytical analysis

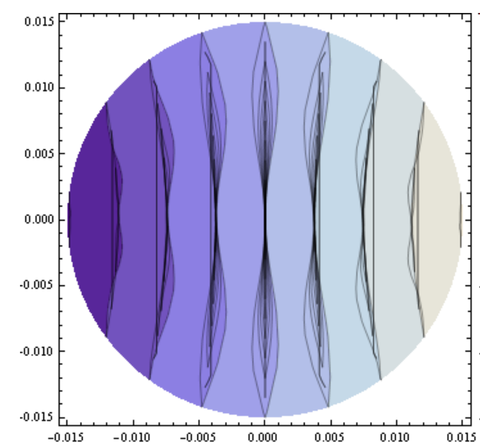
Find Subtended angle, Sensitivity and Linearity





Crosstalk and reflection effects are not taken into account





Isolines of Δ_h/Σ

Example of Stripline optimization

Find Length and other geometry

Coaxial optimization:

Sum mode of the four striplines should be used for proper matching with center beam. EM simulation can be used for the optimization of the sum mode.

Dipole modes are usually not taken into account due to the low strength compared to the sum mode.

Length optimization:

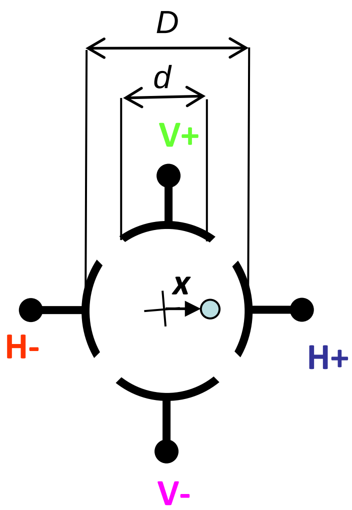
Optimum for 175 MHz narrowband measurement ➡

$$l_{opt} = \frac{c}{2f}\left[1/\beta_w + 1/\beta_s \right] \approx \textbf{78 mm}$$

If BPMs are to be used as well with higher beam harmonics, the optimum length could be a trade-off of the responses at both frequencies

Electromagnetic 3D simulations

Validate and HF 3D effects

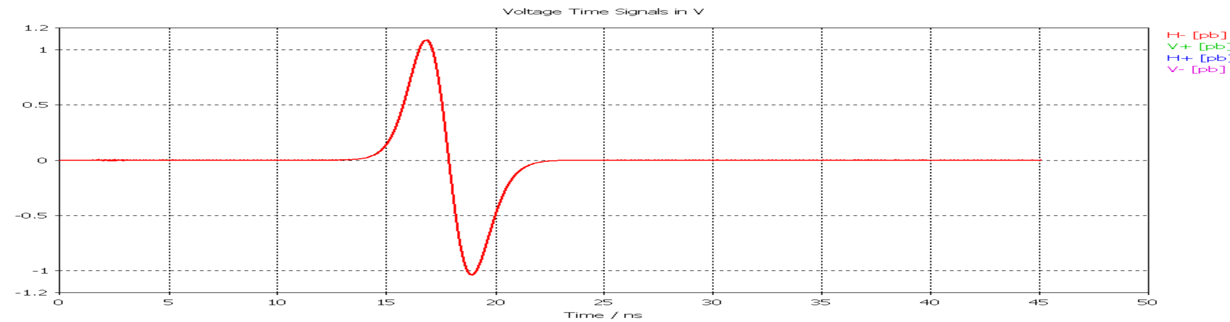


β=0.0728
I= 125 mA
σ= 15 mm

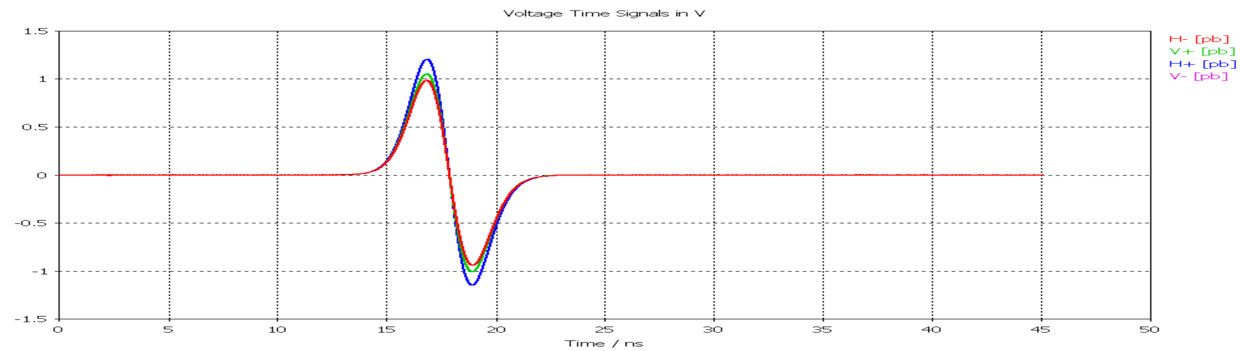
LHC button
d= 24 mm
D= 49 mm

CST Particle Studio simulations

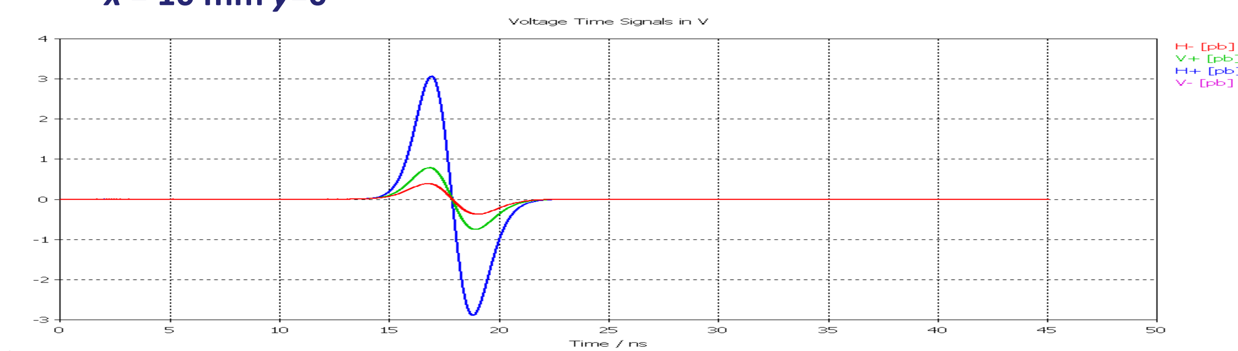
Centered beam



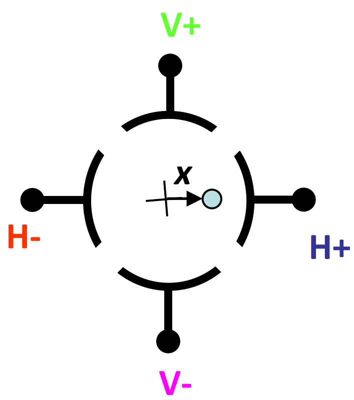
***x* = 1 mm *y*=0**



***x* = 10 mm *y*=0**



Electromagnetic 3D simulations

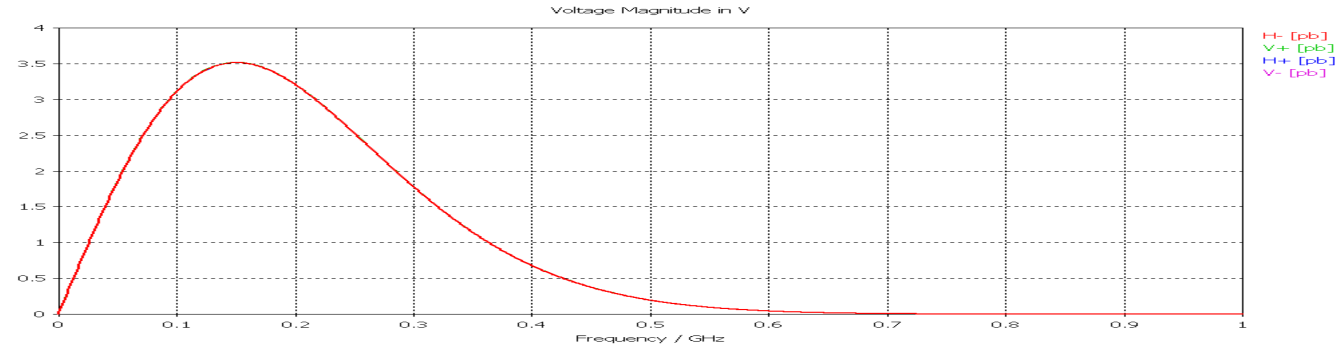


β=0.0728
I= 125 mA
σ= 15 mm

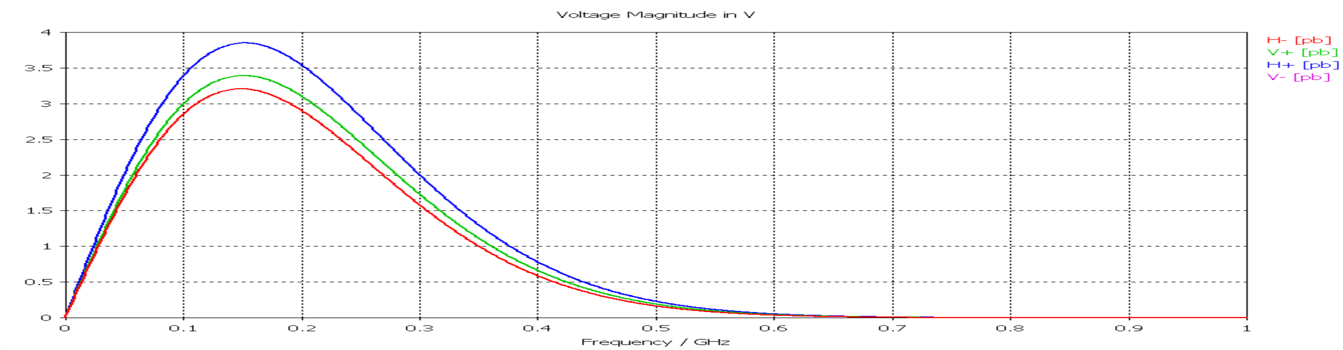
LHC button
d= 24 mm
D= 49 mm

CST Particle Studio simulations

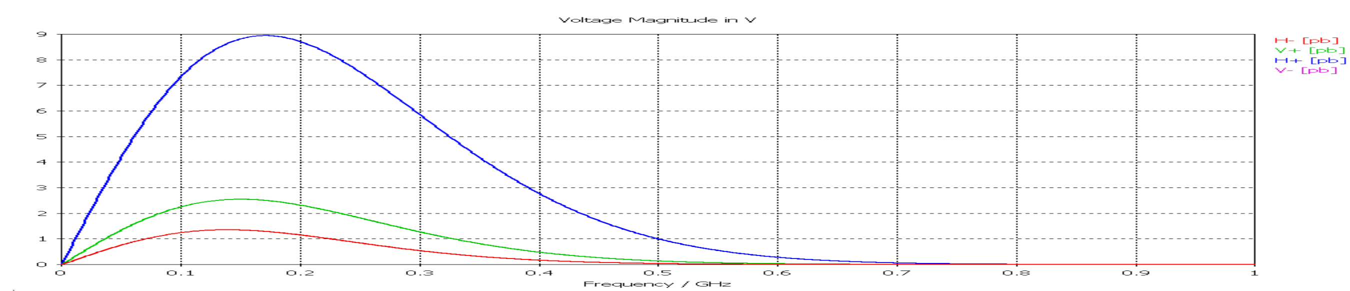
Centered beam



***x* = 1 mm *y*=0**

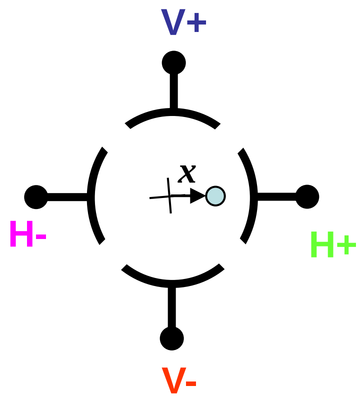


***x* = 10 mm *y*=0**



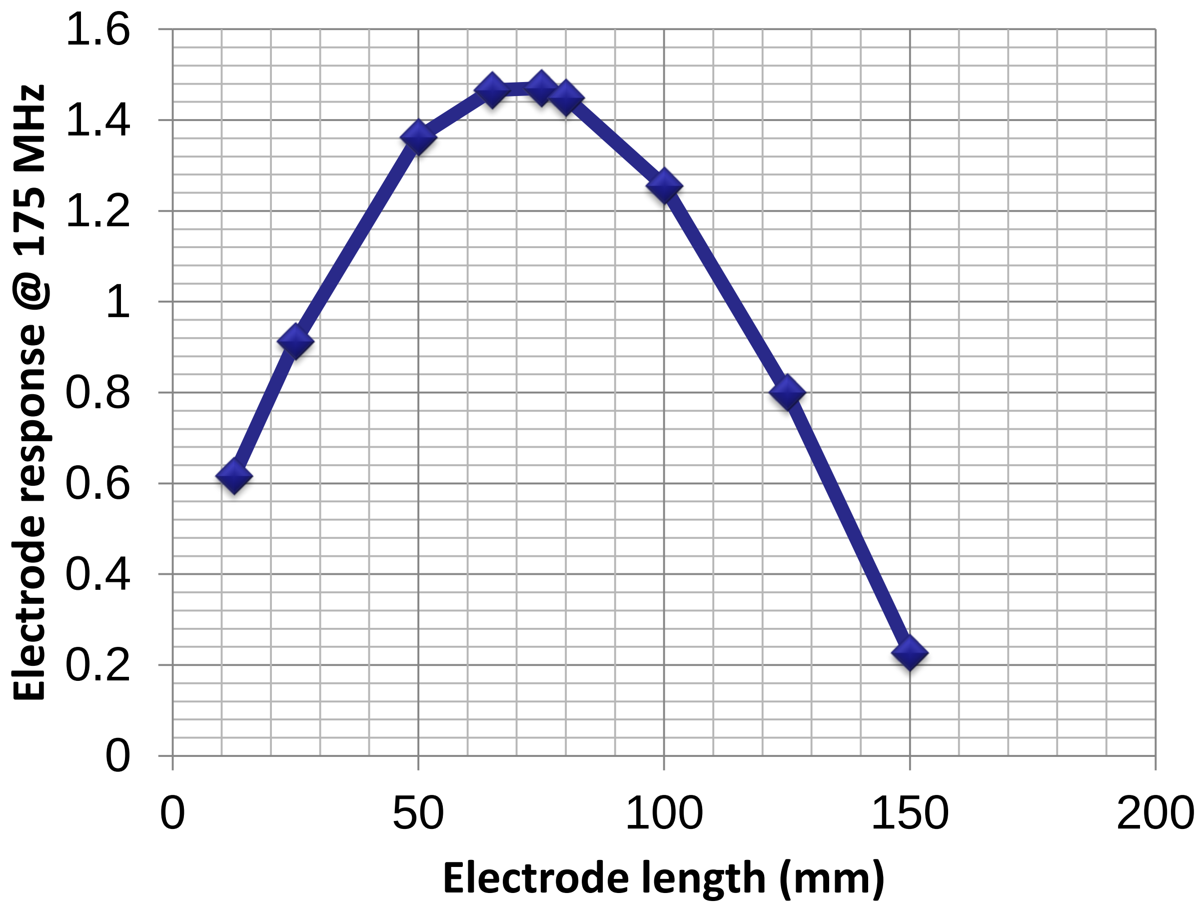
Shift of frequency peak for offset beams -> HF content loss (see Kowina at DIPAC2009)

Capacitive electrode: length study



β=0.0974
I= 125 mA
σ= 50mm
Electrode
D= 150 mm

CST Particle Studio simulations



Electronics software

They can be easily used to simulate the electronics and the pickup together with different kind of stymulus.

Wonderful for optimization of electronics

Good overview of their use for beam position monitors in proceedings of CARE workshop in Lueneburg, November 2006: talks of J.L. Gonzalez, M. Wendt and T. Traber.

Free Circuit Simulators

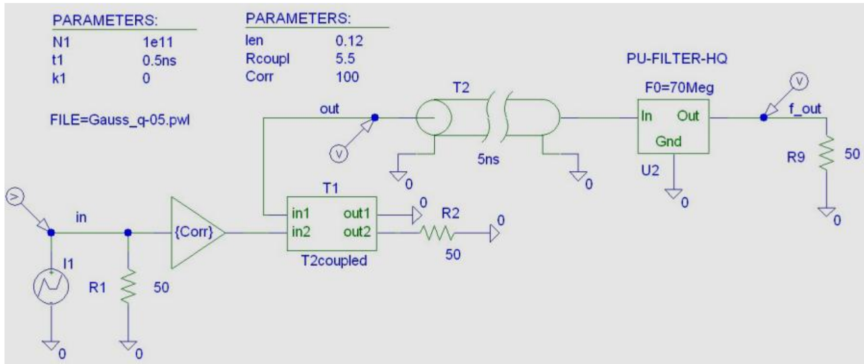
Spice: Berkeley Spice, Spice Opus, Ngspice,TclSpice

Non-spice: eispice, Gnucap, Qucs

Other: Python, Cascade, Meep, Camfr, Octave, SciLab, Ptolemy

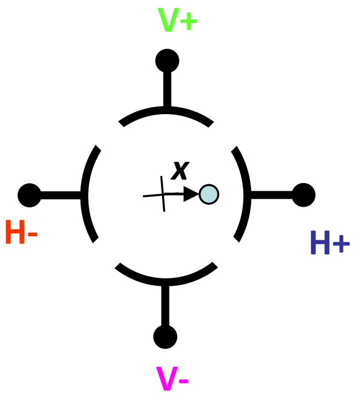
Commercial Circuit Simulators

Orcad, NI Multisim,…



Example of LHC couplet model (J.L. Gonzalez)

Simulations crosscheck

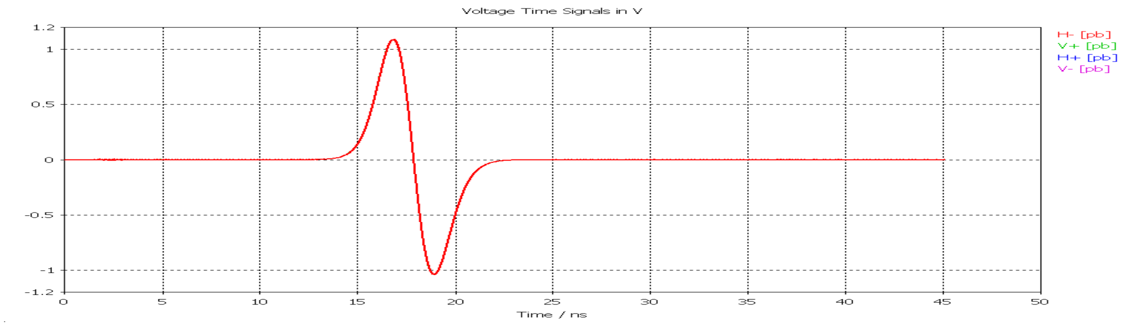


β=0.07
I= 125 mA

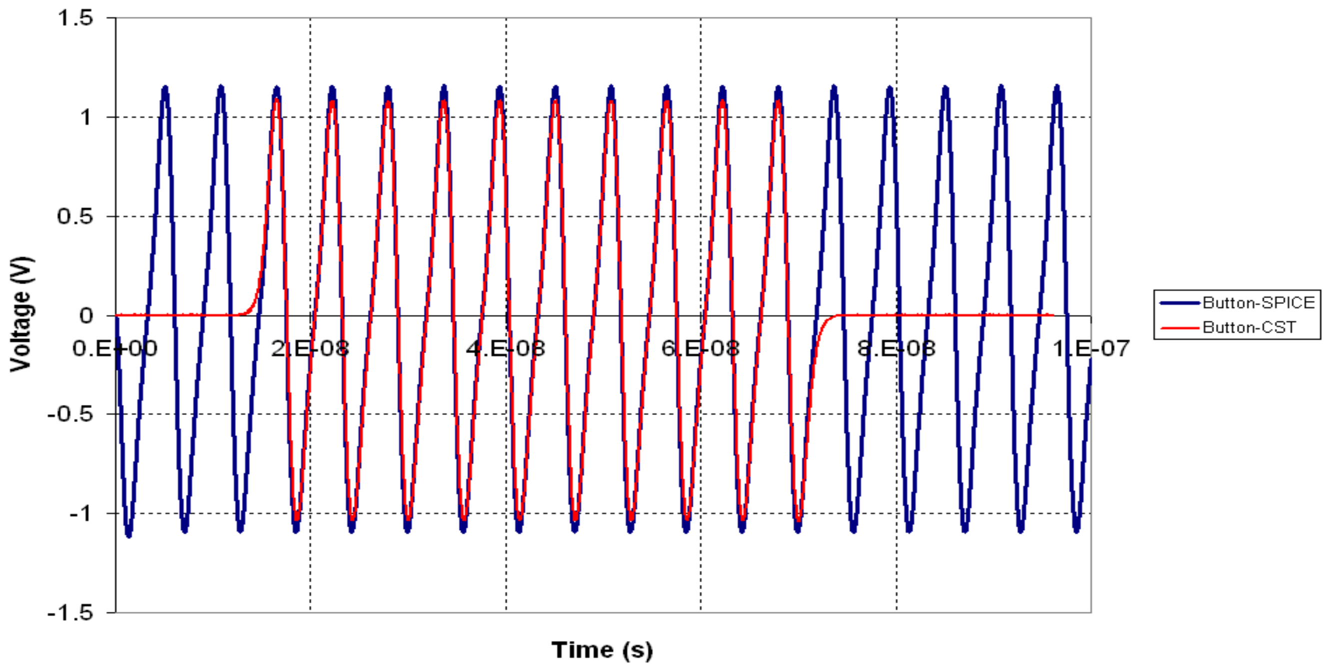
b= 50 mm

Energy *E*	5 MeV
Bunch length σ	15 mm
Simulated $S_{\Delta/\Sigma}$@175 MHz	0.0489 mm^{-1}
Simulated S_{dB}@175 MHz	1.6394 dB/mm
Analytical S_{dB}@175 MHz	1.57984 dB/mm
Simulated $S_{\Delta/\Sigma}$@350 MHz	0.0621 mm^{-1}
Simulated S_{dB}@350 MHz	2.2098 dB/mm
Analytical S_{dB}@350 MHz	2.1856 dB/mm

CST Particle Studio



SPICE



Outline

Mechanical design

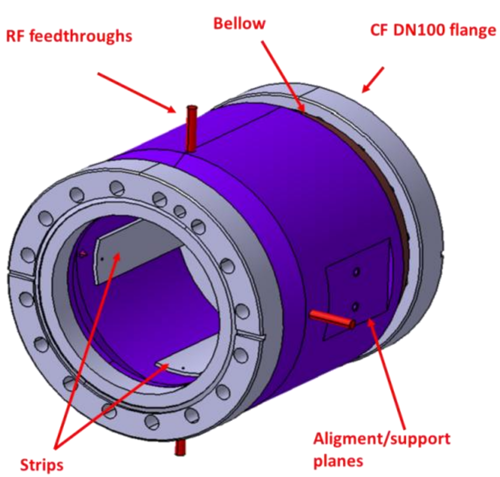
Reminder: simple, cheap and robust assemblies.

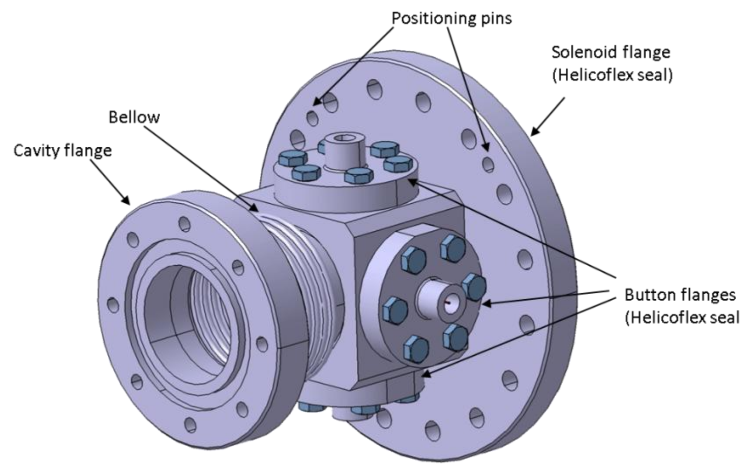
Minimize number of assembly items to increase the machine accuracy.

Foresee alignment plane references and alignment holes for targets.

Removable feedthroughs help the maintenance and replacement of leaking elements.

Bellows and rotatable flanges to facilitate beamline installation and alignment (increase overall accuracy).



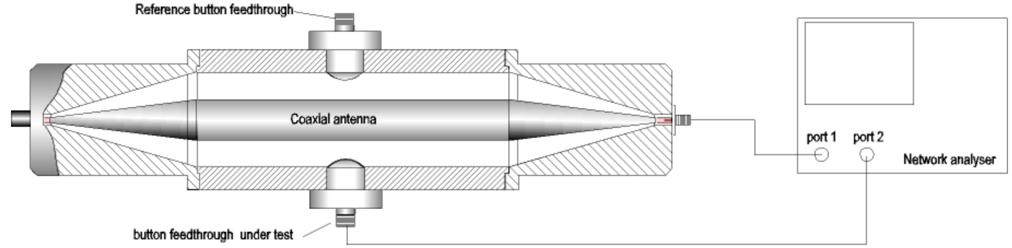


Typical acceptance tests

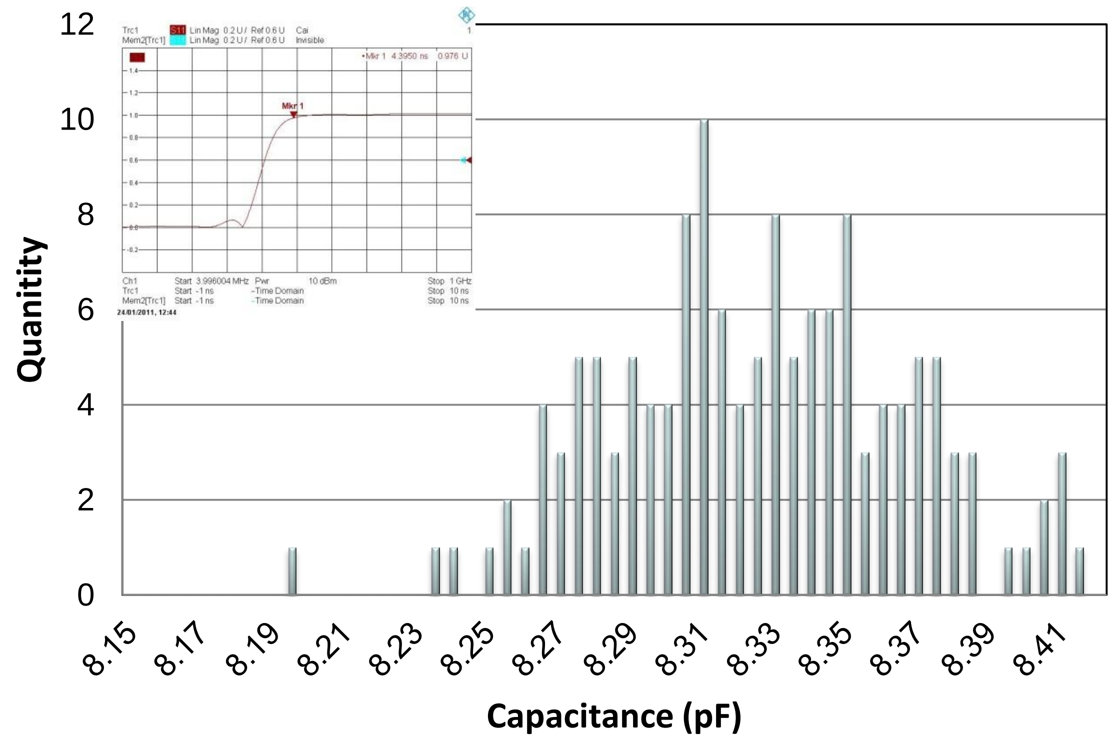
Vacuum leak testing.

Metrology control.

Capacitance pairing at 50 Ω wire setup to obtain better accuracy on the signal strength and position measurement



C. Boccard, CARE proceedings, Lueneburg, 2007

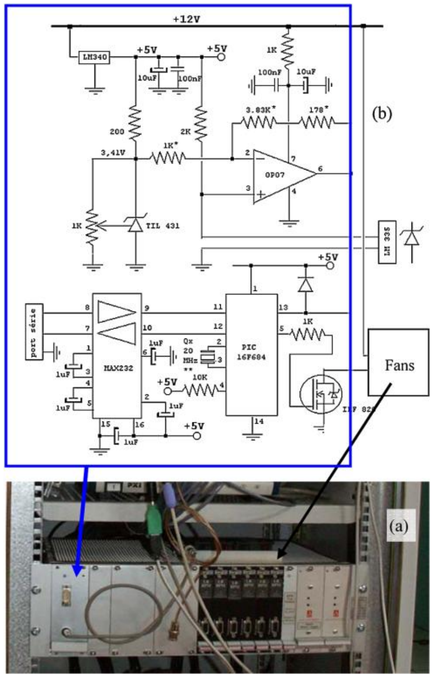


Example of hystogram of a series of measurements of capacitive buttons

- Pickups for low-β beams
- Design workflow
- Electromagnetic design
- Manufacturing
- **Electronics**
- Test bench
- Overview

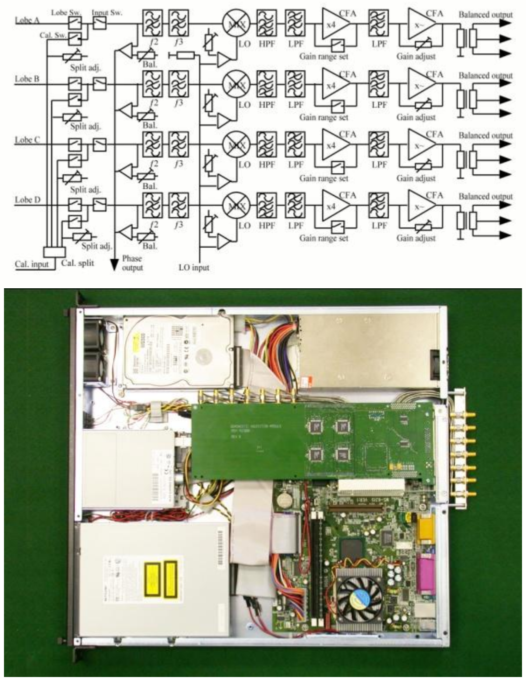
Electronics design

See C. Jamet talk



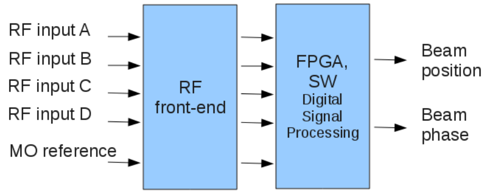
IPHI Bergoz board: Log-ratio, no phase information

M. Cohen, 10.1103/PhysRevSTAB.13.032801



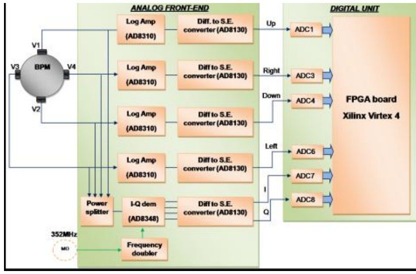
SNS: IF + digital IQ demodulation

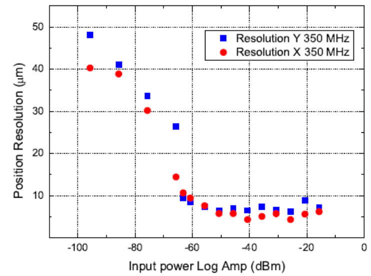
J. Power, PAC'03

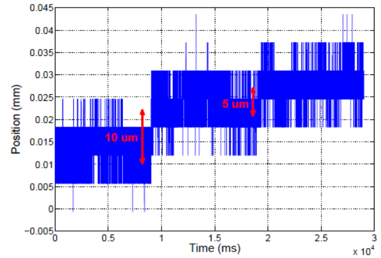


Libera Single Pass H: undersampling

M. Znidarcic, DIPAC11







ESS-Bilbao: Log amps + digital IQ

D. Belver, DIPAC11

LINAC4: IF+ IQ demodulation (J. Tan, DIPAC11)

SPIRAL2: undersampling (P. Ausset yesterday talk)

...

- Pickups for low-β beams
- Design workflow
- Electromagnetic design
- Manufacturing
- Electronics
- **Test bench**
- Overview

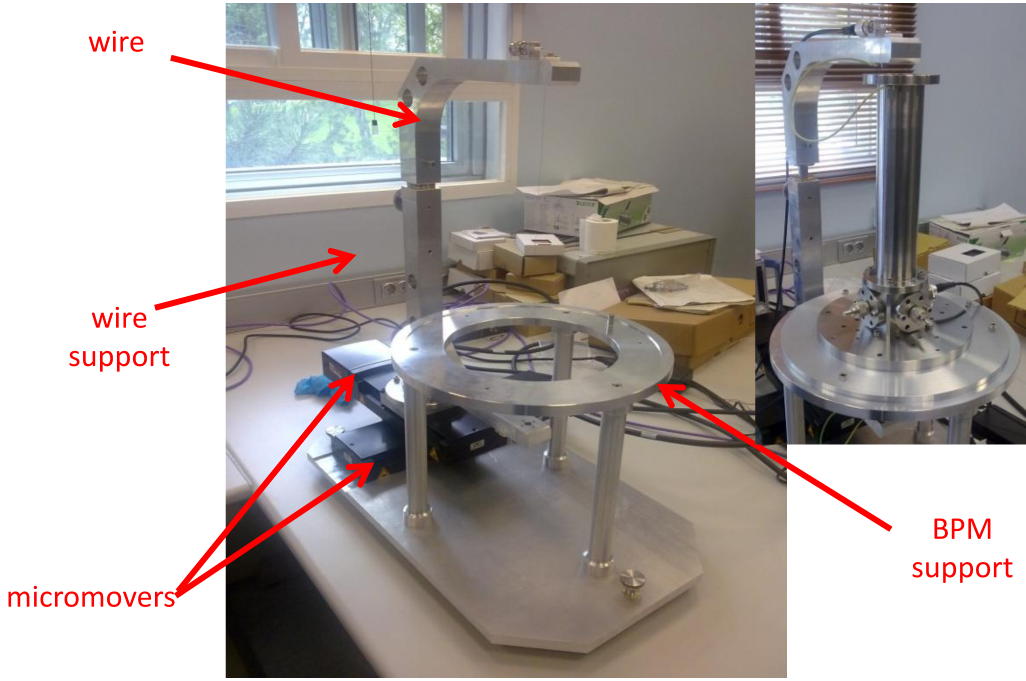
Test bench design

It is not straight forward to extrapolate the wire method results to low-beta beams but...

Wire test benches are very useful to characterize and validate BPM's for validation and characterization

It will be possible to characterize some parameters of the BPM's like:

- Electrical center.
- Sensitivity.
- Linearity.
- Resolution.
- Mechanical and electrical stability.



CIEMAT test bench

Or try to construct a low beta wire test bench…

F. Caspers et al., A new bench method to simulate electromagnetic fields of slow beams, EPAC 90, CERN-PS-90-35

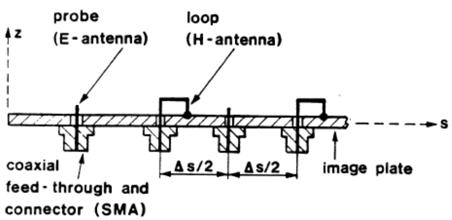
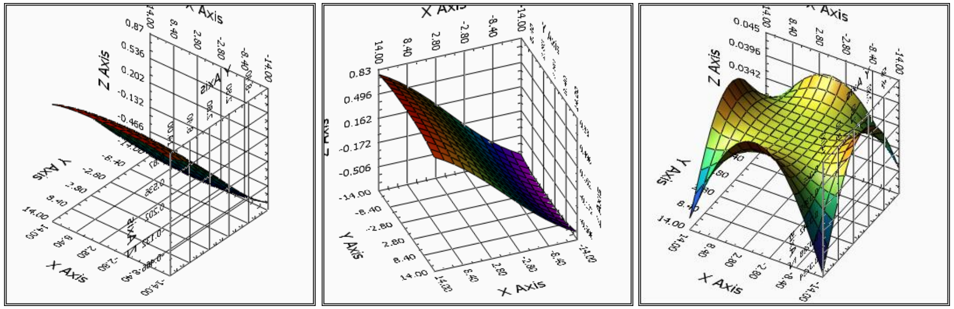


Fig. 1 : Cross-section of the beam-simulator.

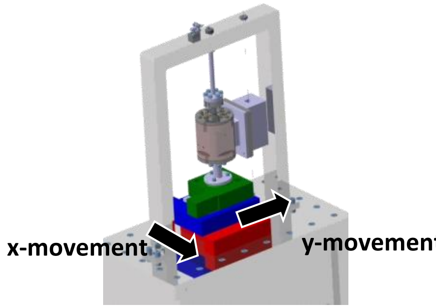


Plot of Δ/Σ in horizontal and vertical and Σ

Low beam-velocity correction

The bunched beam fields deforms such that the BPM offset, sensitivity, and 3rd-order terms will be slightly different from those acquired by the mapping fixture. A technique is necessary to correct these terms for low velocity beams and has been verified with beam experiments (see plot)*.

Example of test bench for 2D field mapping



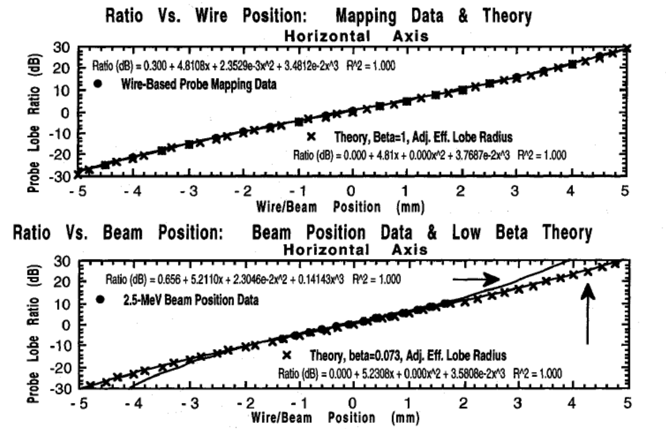


Fig. 6. The top graph compares the theory from Eqs. 3 and 4 with the wire-based probe-mapping data with the effective lobe radius adjusted to agree with the probe-mapping data. The bottom graph shows the equivalent beam data and theory for a 2.5 MeV beam.

The technique consists of the following steps:

1. With β=1, adjust the electrode subtended angle and radius in the analytic model so that a new model based map agrees with mapping fixture data.
2. Decrease β in the analytic model to agree with the expected beam velocity.
3. Produce new analytically-derived map.
4. Perform forward and inverse least-squares fits.
5. Change manufactured offsets in the initial mapped data by using the new low-β BPM sensitivity.

$$i_w(b,\phi_w,t) = \frac{-I_b(t)}{2\pi b}\left[1+2\sum_{m=1}^{\infty}\left(\frac{r}{b}\right)^n \cos[m(\alpha-\theta)]\right] \qquad X = \sum_{j=0}^{N2}\sum_{i=0}^{N1} a_{ij} X^i Y^j$$

$$i_w(\omega,r,\theta,\alpha) = \frac{A_n\langle I_b\rangle}{\sqrt{2}\pi b}\left[\frac{I_0(gr)}{I_0(gb)} + 2\sum_{m=1}^{\infty}\frac{I_m(gr)}{I_m(gb)}\cos[m(\alpha-\theta)]\right]$$

$$X = \sum_{j=0}^{N2}\sum_{i=0}^{N1} a^{\beta} X^i Y^j$$

* J. D. Gilpatrick, et al., "Experience with the Ground Test Accelerator Beam-Measurement Instrumentation," AIP Conf. Proc. 319, Santa Fe, NM, pp 154-169, May, 1993.

Beam-based alignment

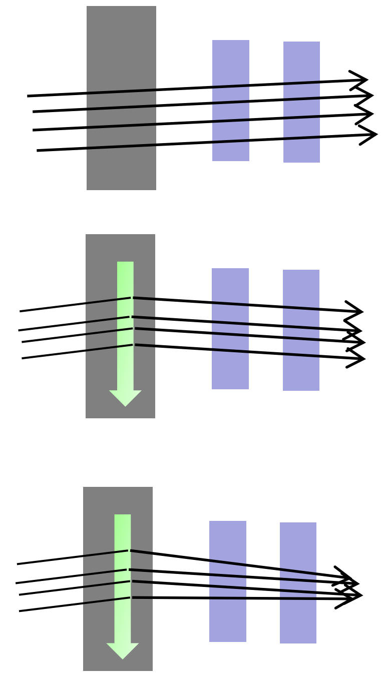
To precisely find the electrical offsets with respect to the magnetic center of the quadrupoles, the beam-based alignment procedure implemented in the J-PARC accelerator can be used which can obtain **up to tens of micrometers of accuracy** for each BPM* . The method consists of:

1. **Move the beam by an steering magnet** located in upstream.
2. For each steered beam, **vary the Q-Magnet field**.
3. Monitor whether downstream beam position (BPM(N+1)th) is varying or not. If varying, **measure the dependence *s* defined by the following formula**:

$$s = \frac{dx_{N+1}}{dQ_N}$$

where x_{N+1} is the position at the BPM N+1, and Q_N is the magnet strength N.

4. **Interpolate the beam position by BPM(N)th, where the slope is zero**. The obtained position is the offset parameter by the beam based calibration for the BPM(N)th.



* S. Sato et al. *Beam Position Monitor and its Calibration in J-PARC LINAC*. Proceedings of PAC'07, 2007.

Pickups for low-β beams

Design workflow

Electromagnetic design

Manufacturing

Electronics

Test bench

Overview

Overview

Electromagnetic pickups are not “ideal” instruments for low beta beams but are essential for beam operation.

They are still the most simple, fast and accurate measurement of the beam center.

Signal is degratated due to the low-velocity but it is still convenient for operation.

Many topics missing: cables, filtering, stripline and buttons theory,...

Still room for developments in the field of electronics, calibration and characterization.

That’s all!

QUESTIONS?

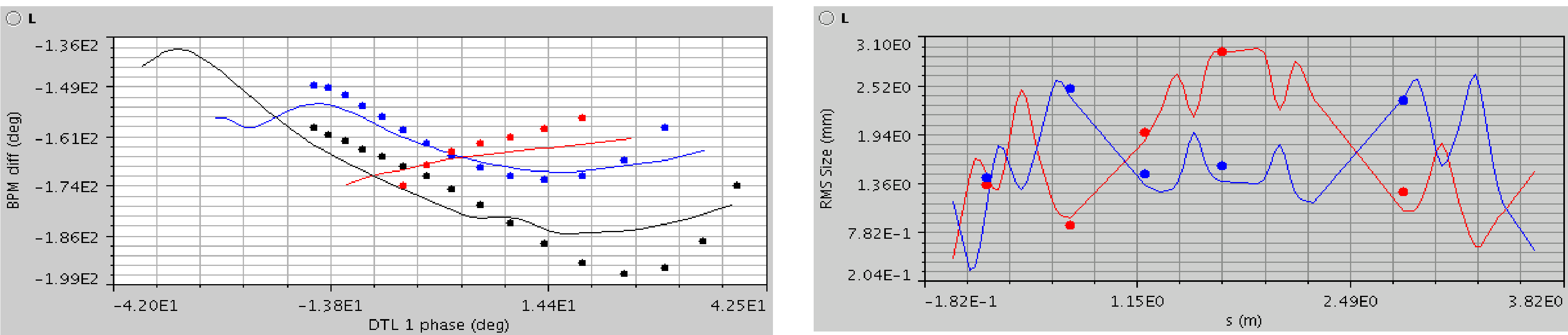
Control system

A stable and robust link with the CCS is mandatory to ensure successful and operable instruments.

In hadron LINACS the most extended tools are: EPICS and FESA.

BPMs in LINACs are usually low speed signals, with 1-2 Hz refresh time + post-mortem data available.

For example, XAL application as platform to control the accelerator in EPICS.



SNS BPM application