Finite Element Method Simulations - a Powerful Tool for Beam Position Monitor Design

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Outline

Linear cut (Shoe-box) BPM

- ***Detection principle and examples of technical realization***
- ***FEM simulations of BPM features:***
  - ***simulation of cross-talk***
  - ***optimization of position sensitivity***
  - ***frequency dependence of position sensitivity***

Capacitive button BPMs

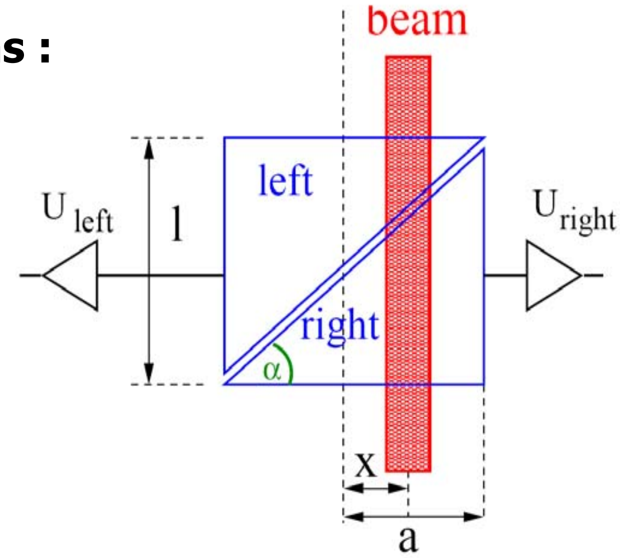
- ***FEM simulations for low β beam:***
  - ***signal shape and its frequency spectrum***
  - ***position sensitivity***
  - ***sensitivity map***

Summary

Shoe-box BPM

Typical beam parameters in proton/ion synchrotrons :

Frequency range: 1 MHz < f_{rf} < 10 MHz
⇒ bunch-length >> BPM length



Advantage (in ideal case):

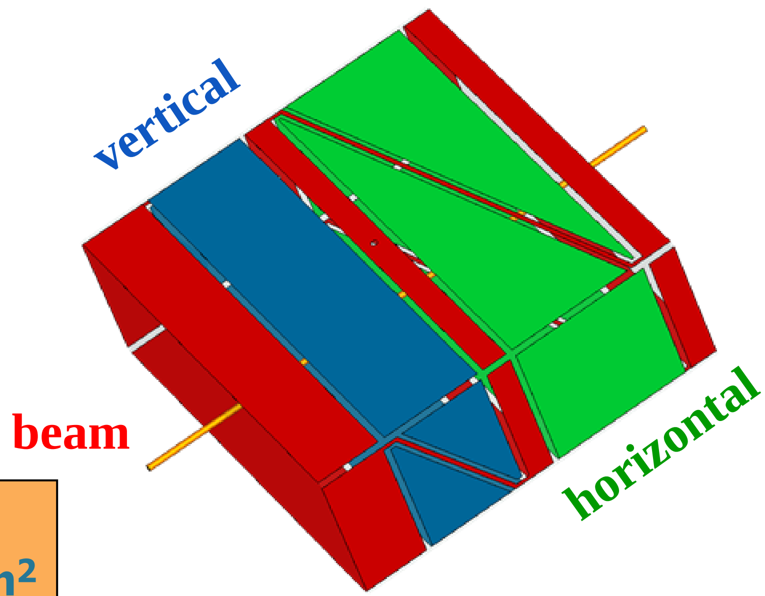
- *very linear position reading*

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

- *frequency independent position sensitivity*
- *precise position determination even for transversal large beam*

Disadvantage:

- *large size*
- *complex mechanics*

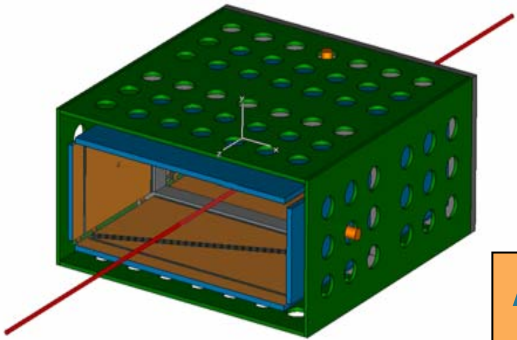


Aperture: 180x70 mm²

Examples for technical realization

Technical realization for HIT synchrotron

(design based on metal coated Al_2O_3 ceramic plates)



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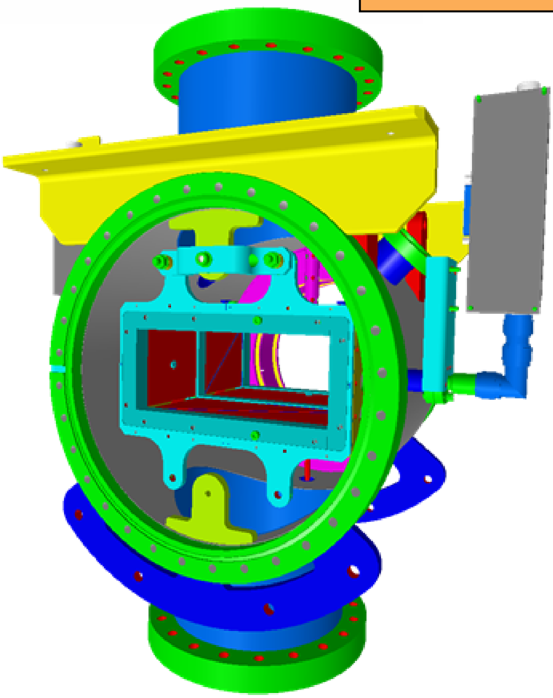
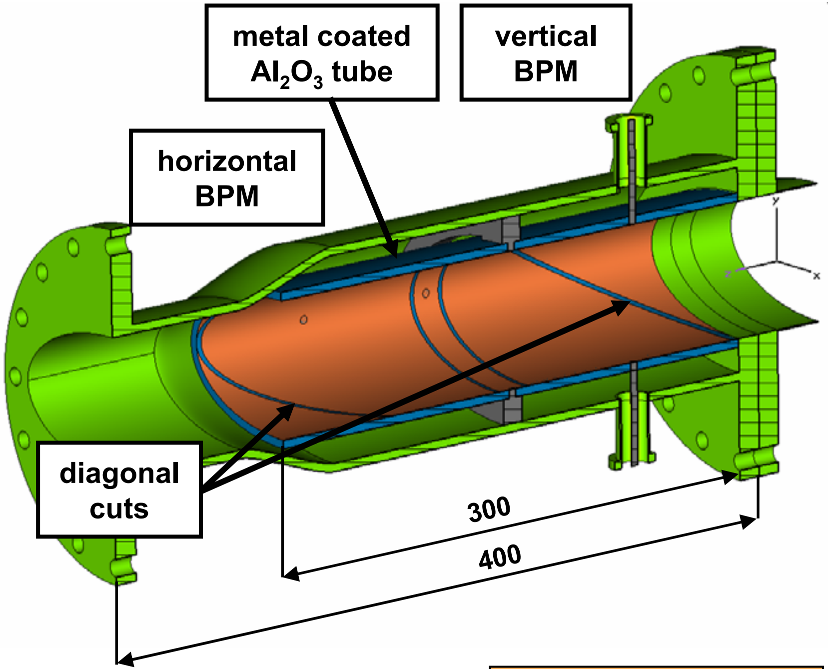


Design for FAIR SIS 100 BPM

(same properties as shoe-box)



Aperture: 135x65 mm²

FAIR facility: M. Schwickert,WEOA04

Real life $\Rightarrow$ FEM simulations required

Available Software: CST-Suite (MAFIA), Comsol, HFFS, MAGIC

Considerations (here):

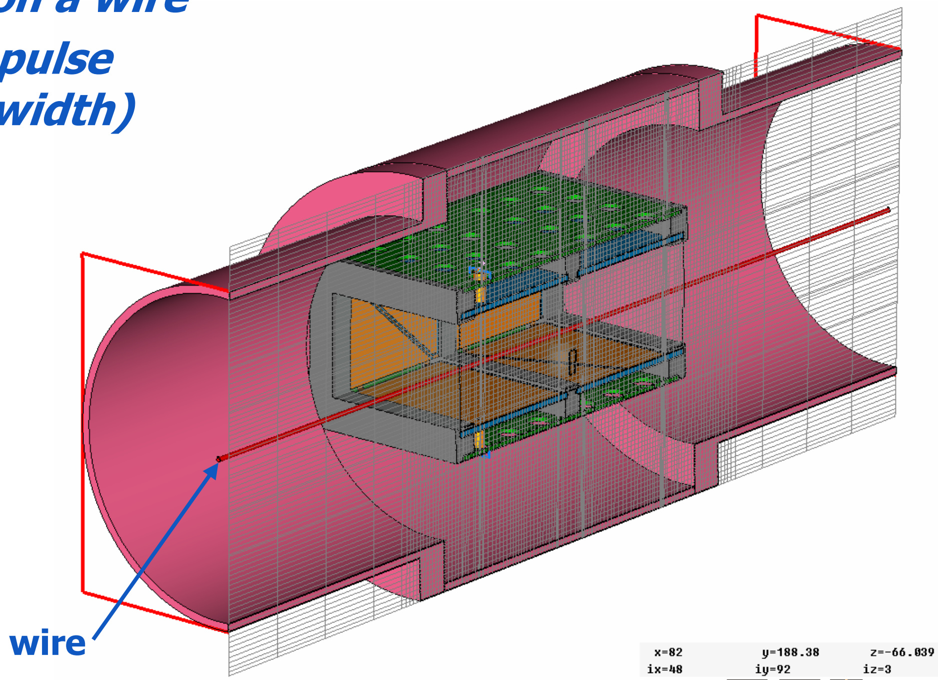
- *frequency range: 1 MHz < f_{rf} < 10 MHz*
- *bunch-length >> BPM length*

$\Rightarrow$ *propagation of E-field can be approximated by TEM wave*

FEM simulations:

- *volume divided in 3-dim meshes with typically 10^6 to 10^7 cells*
- *beam is simulated by a traveling wave on a wire*
- *Time Domain Solver: Gaussian shaped pulse (width corresponding to 200 MHz bandwidth)*
- *Output: time dependent signal, frequency dependences, S-parameters, field distribution etc.*

Simulation time ~15 h / task

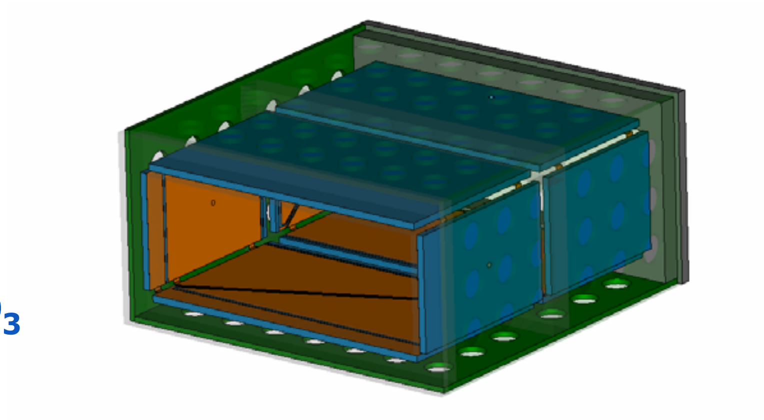


Ceramics VS. metal plates (simulations of cross-talk)

Advantage:

- *high mechanical stability*
- *low expansion coefficient=> not sensitive on temp. changes*
- *even complicated structures possible*

Design based on metal coated ceramics



Disadvantage:

- *high coupling capacitance due to* $\varepsilon=9.6$ for Al_2O_3

  $\Rightarrow$ *deterioration of position sensitivity*

Geometry	Structure on ceramics	Metal plates
no guard ring 1mm gap	-5.1dB	-7.9dB
no guard ring 2mm gap	-8.1dB	-10.8dB

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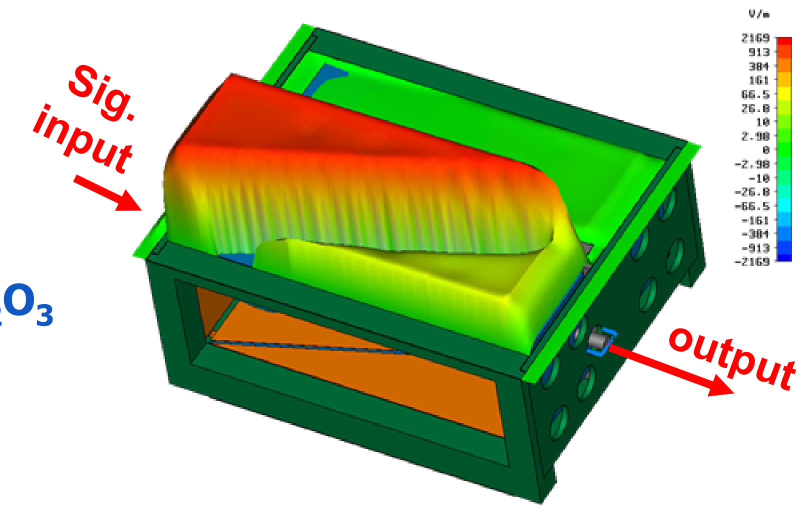

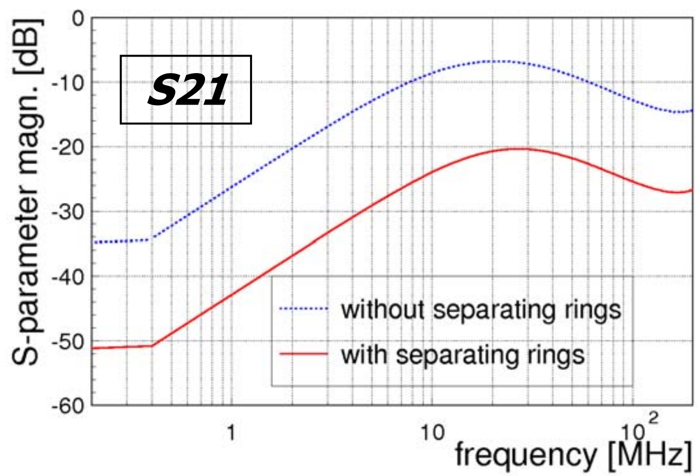

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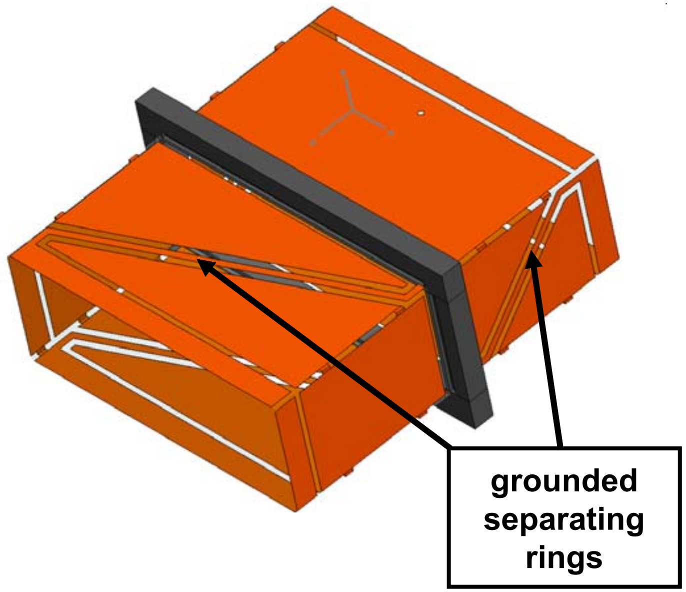
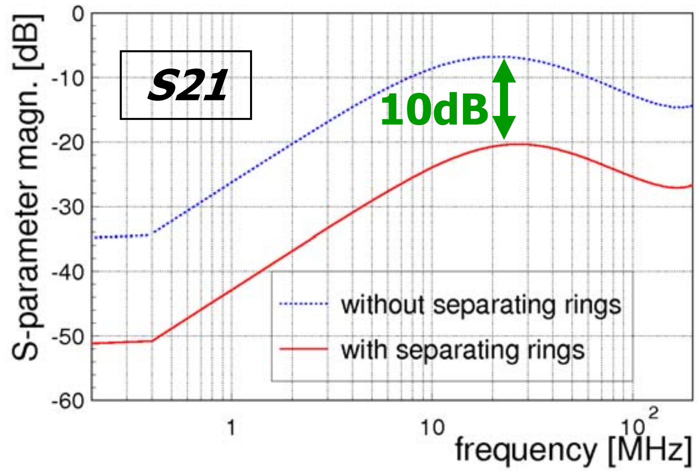
- *high coupling capacitance due to* ε=9.6 for Al_2O_3
  ⇒ *deterioration of position sensitivity*

Geometry	Structure on ceramics	Metal plates
no guard ring 1mm gap	-5.1dB	-7.9dB
no guard ring 2mm gap	-8.1dB	-10.8dB
with guard ring	-20.8dB	-22.5dB

- *capacitance can be reduced by ~factor of 3 by mean of separating ring*

Design based on metal coated ceramics





Optimization of Position Sensitivity

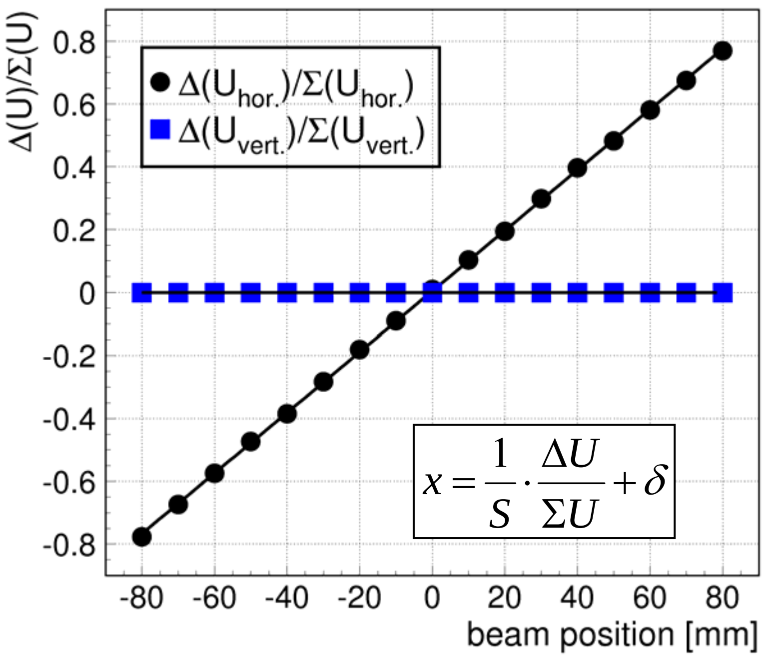
Simulations:

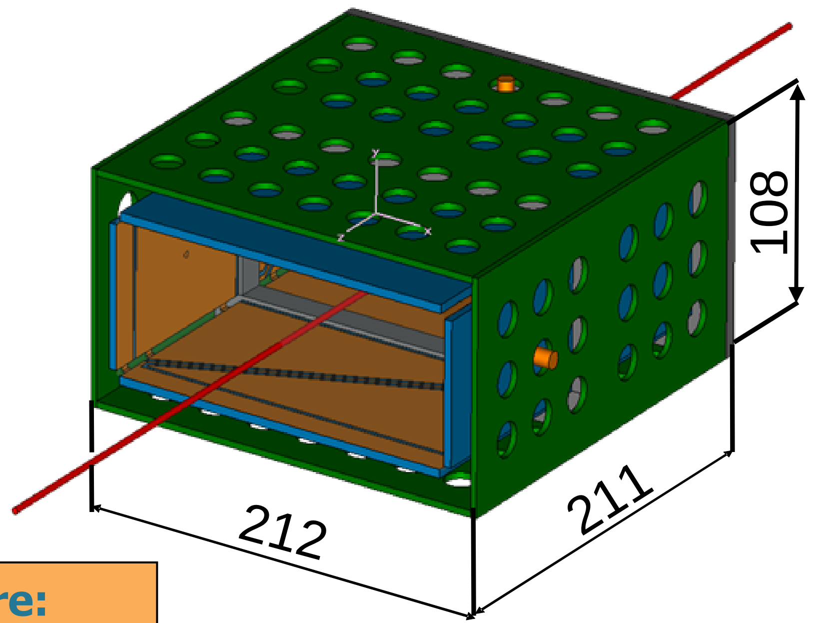
- ***Gaussian pulse travels on wire on different positions***
- ***calculation of $\Delta U/\Sigma U$*** **from** ***induced voltage on matched output ports***

Criteria of optimization:

- ***linearity***

  is typical for shoe-box BPMs but
  can be spoiled e.g. by structure discontinuities
  (max. error ± 1% for BPM in ± 80 mm displacement range)





Aperture:
180x70 mm^2

Optimization of Position Sensitivity

Simulations:

- ***Gaussian pulse travels on wire on different positions***
- ***calculation of $\Delta U/\Sigma U$*** **from** ***induced voltage on matched output ports***

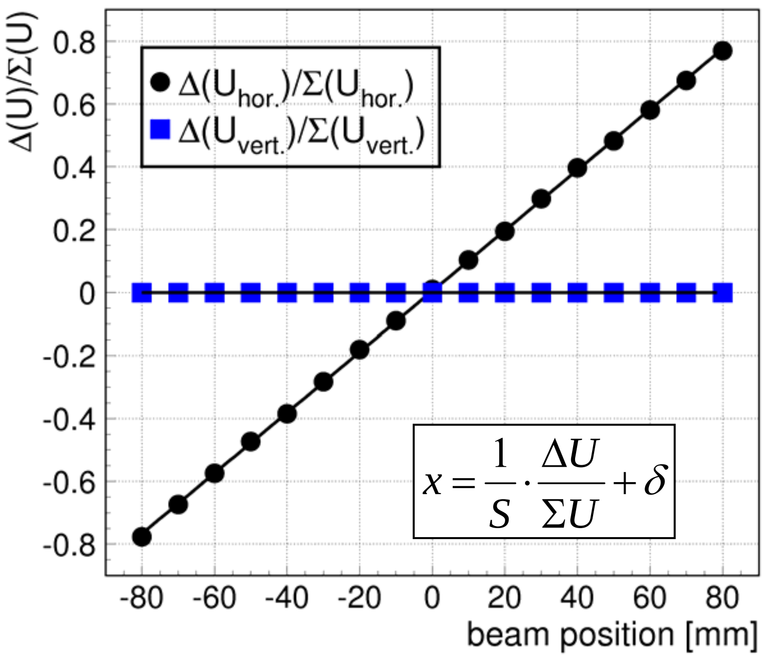
Criteria of optimization:

- ***linearity***
- ***sensitivity***

  increased by factor of two (!) by cross-talk reduction:
  (additional separating ring between adjacent electrodes)

  Sx=0.96 %/mm (ideal value Sx=1.1 %/mm) at 1 MHz

  Sy=2.6 %/mm (ideal value Sy=2.9 %/mm) at 1 MHz



Aperture:
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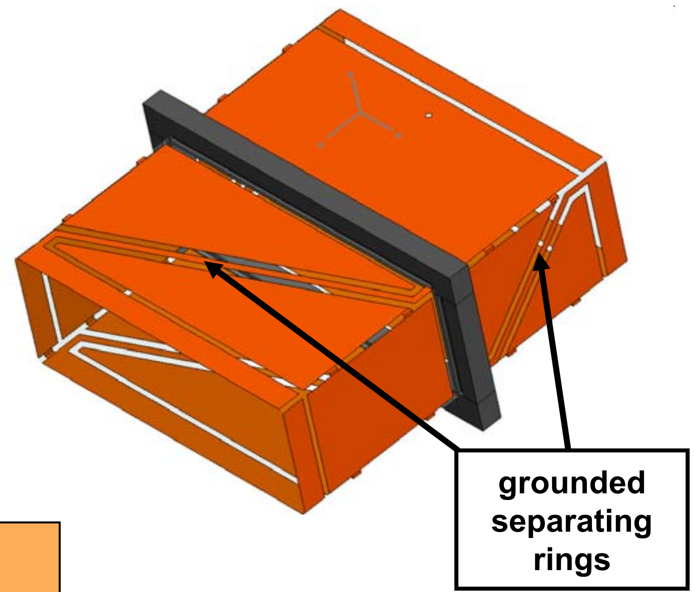


Optimization of Position Sensitivity

Simulations:

- *Gaussian pulse travels on wire on different positions*
- *calculation of $\Delta U/\Sigma U$* from *induced voltage on matched output ports*

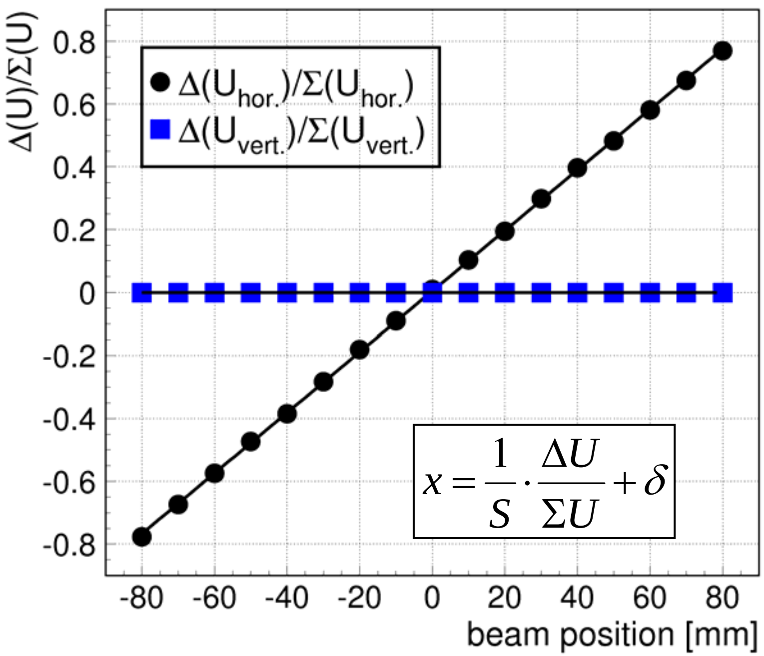
Criteria of optimization:

- *linearity*
- *sensitivity*
- *offset reduction*

  symmetrical and well grounded guard rings

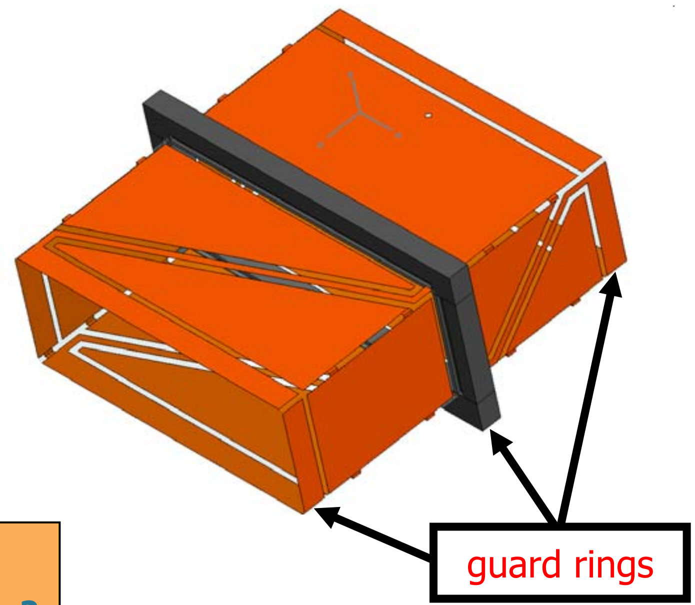
  δx=-0.4mm (ideal value δ=0) at 1 MHz

  δy=-0.04mm (ideal value δ=0) at 1 MHz



$$x = \frac{1}{S} \cdot \frac{\Delta U}{\Sigma U} + \delta$$

Aperture: 180x70 mm^2



Optimization of Position Sensitivity

Simulations:

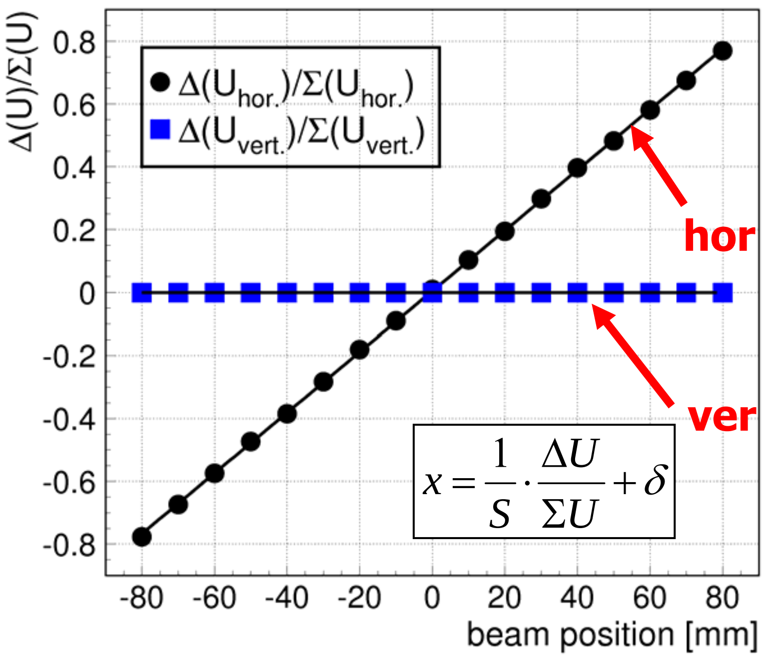
- *Gaussian pulse travels on wire on different positions*
- *calculation of $\Delta U/\Sigma U$* from *induced voltage on matched output ports*

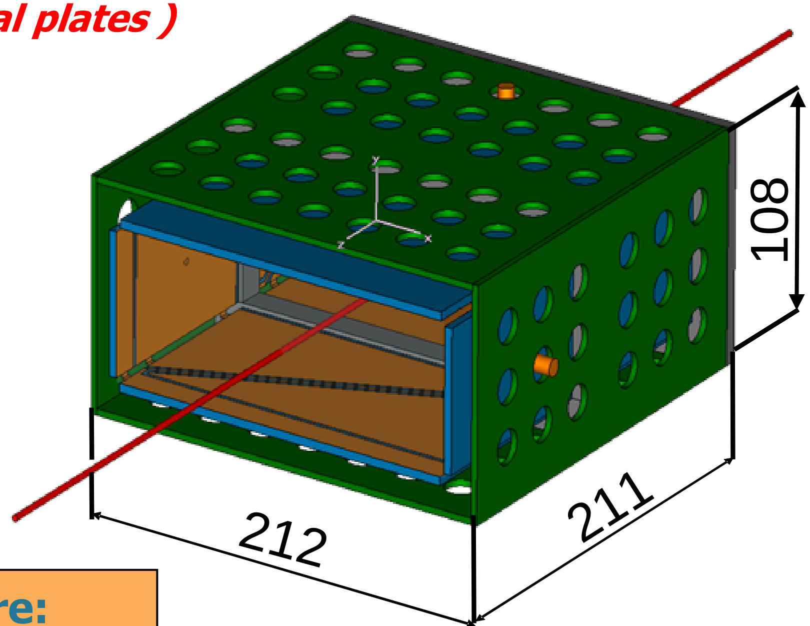
Criteria of optimization:

- *linearity*
- *sensitivity*
- *offset reduction*
- *x-y plane independence*

  careful treatment of fringe fields

  $\Rightarrow$ horizontal displacement not seen in vertical plates)

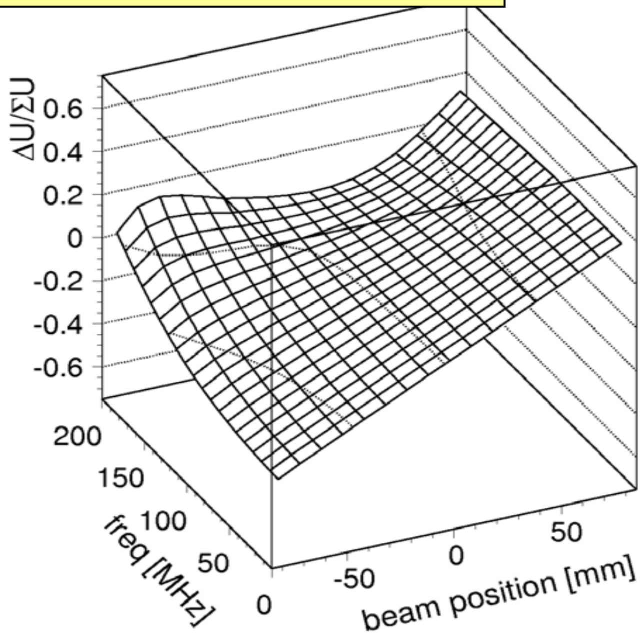




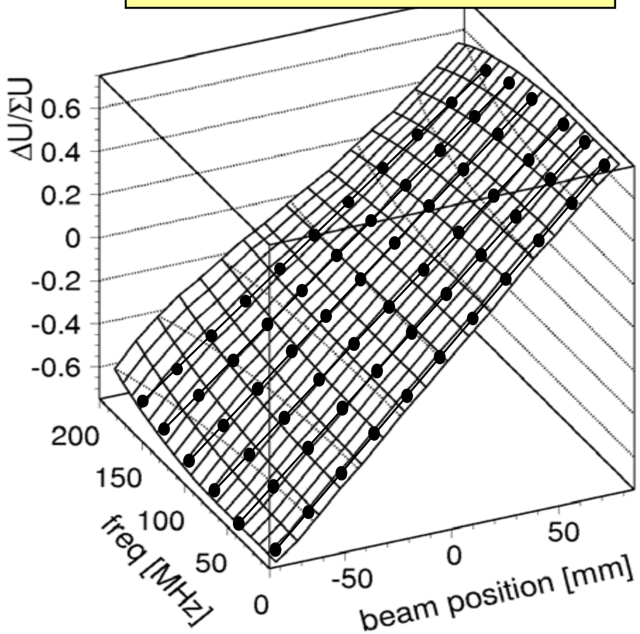
Aperture:
180x70 mm^2

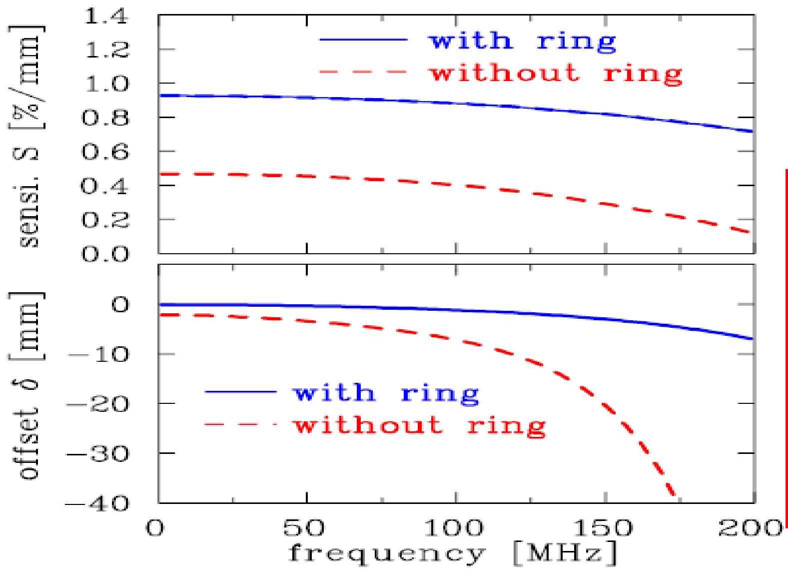
Frequency dependence of position sensitivity

Without separating ring



With separating ring





$$x = \frac{1}{S(\omega)} \cdot \frac{\Delta U}{\Sigma U} + \delta(\omega)$$

- **only with separating rings position sensitivity is nearly frequency independent**
- **sensitivity with separating rings is a factor of two larger as without ring.**
- **offset with separating ring is almost constant up to 100 MHz**

FEM simulations of button BPMs (FAIR p-Linac)

Ansatz:

- *different β along lattice*
- *position measurements on n^th rf harmonics (rf leakage in inter-tank sections)*

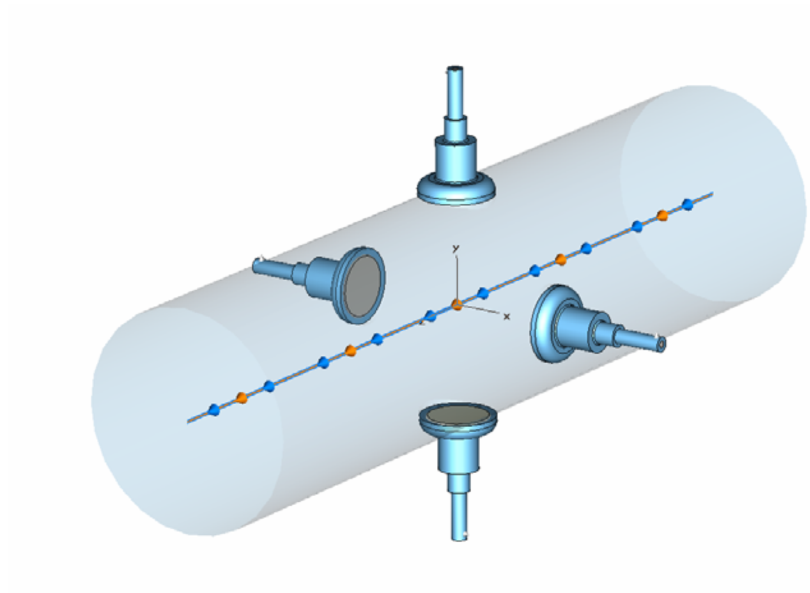
Parameters:

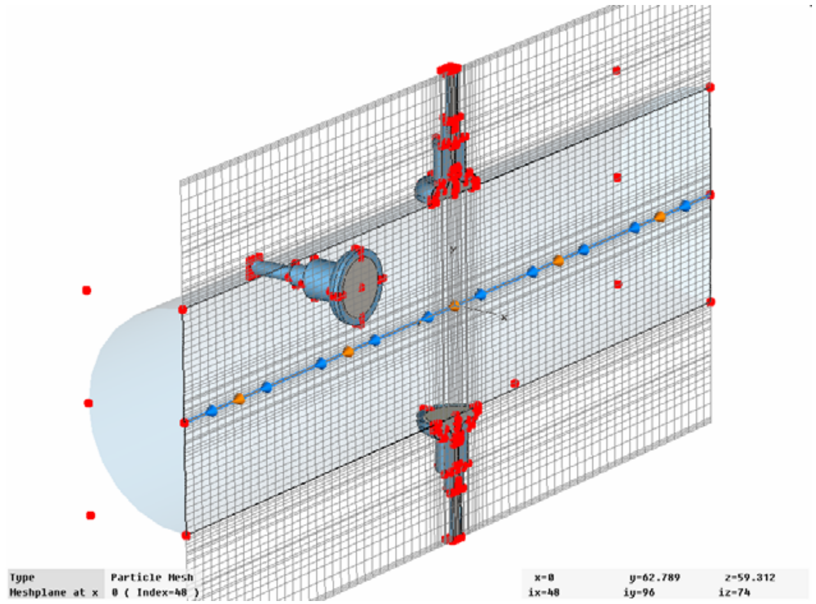
- *BPM aperture: Ø 30 mm*
- *f_{rf} = 325 MHz*
- *bunch length σ_t = 150 ps*

Simulations:

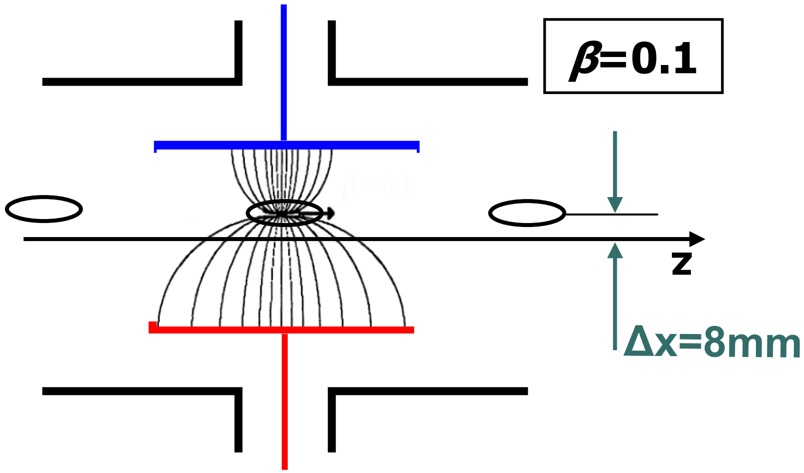
- *CST Particle Studio used*
- *beam simulated as Gaussian charge distribution with:*
  - *bunch length σ_t = 150 ps*
  - *velocity $0.1 < \beta < 0.3$*
- *Weak Field Solver used*
- *~1.8×10^6 mesh cells*

Simulation time ~20 h / task





FEM simulations for low β beam

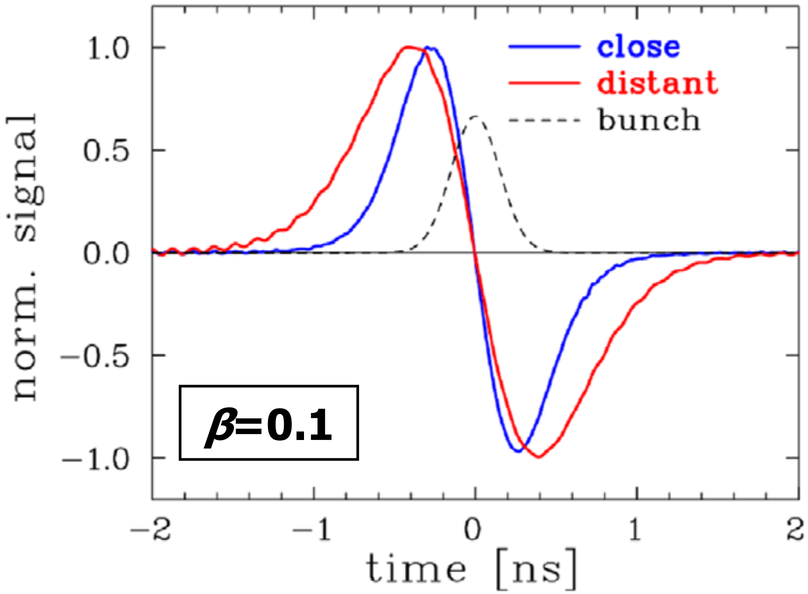


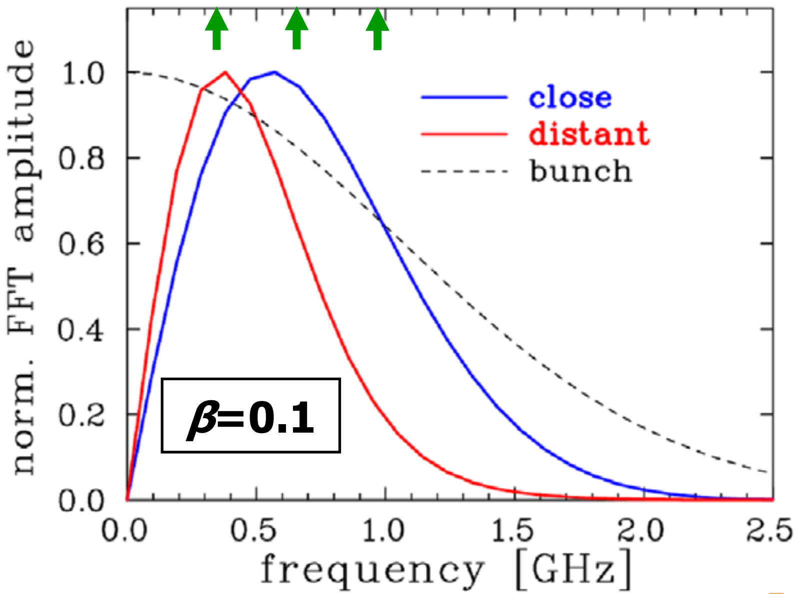
Parameters:

- ***BPM aperture: Ø 30 mm***
- ***f_{rf} = 325 MHz***
- ***bunch length σ_t = 150 ps***

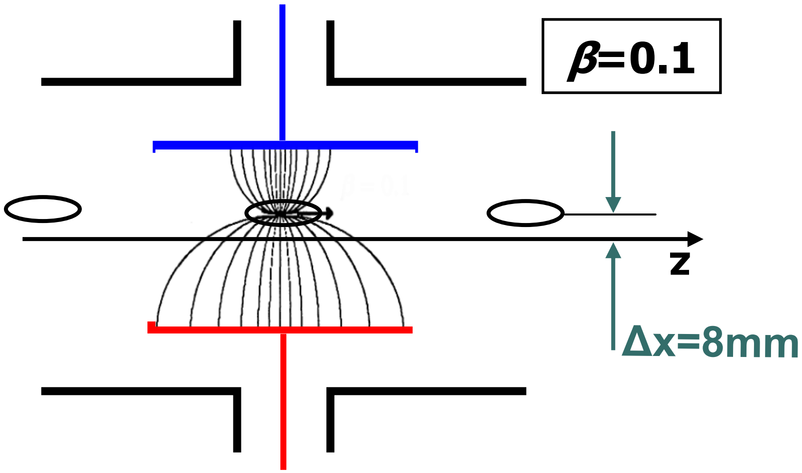
Results:

- ***signal shape and its frequency spectrum depends on beam position***





Position sensitivity for low β beam



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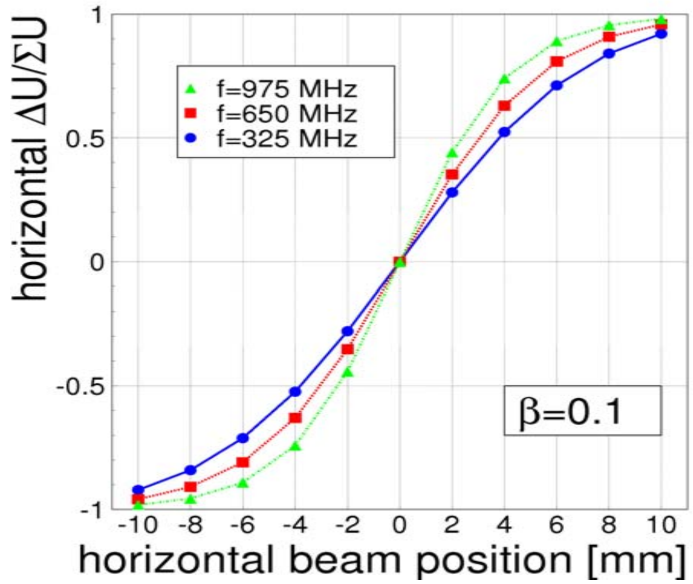
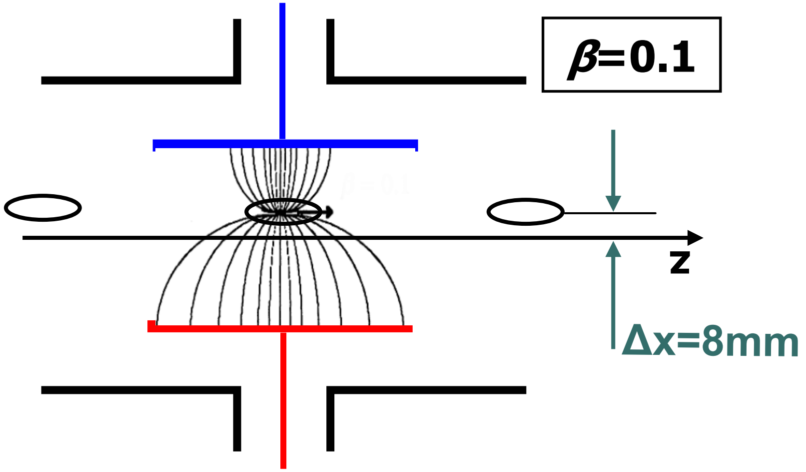


Results:

- *signal shape and its frequency spectrum depends on beam position*
- *position sensitivity depends on frequency (chosen rf harmonics)*

Position sensitivity for low β beam



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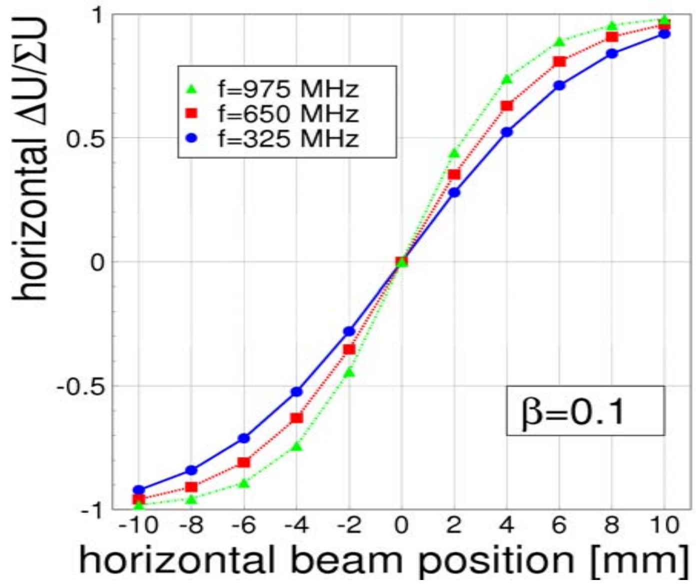
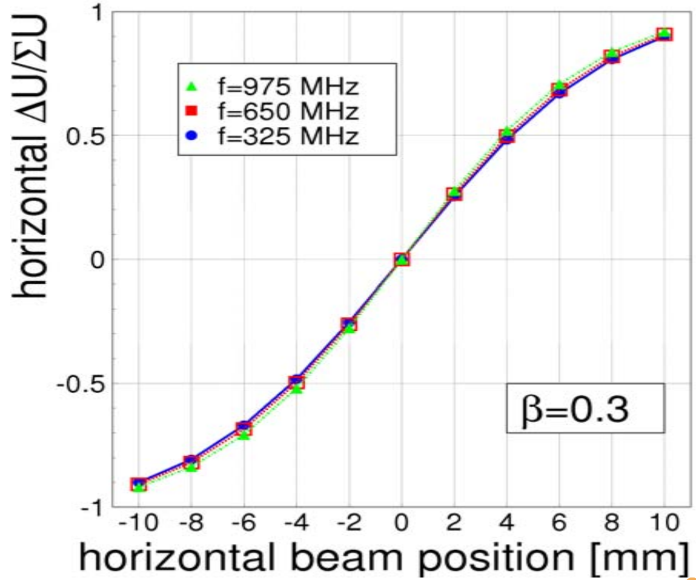
Results:

- *signal shape and its frequency spectrum depends on beam position*
- *position sensitivity depends on frequency (chosen rf harmonics)*
- *position sensitivity depends on β*
- *readouts are non-linear (typically for button BPM)*





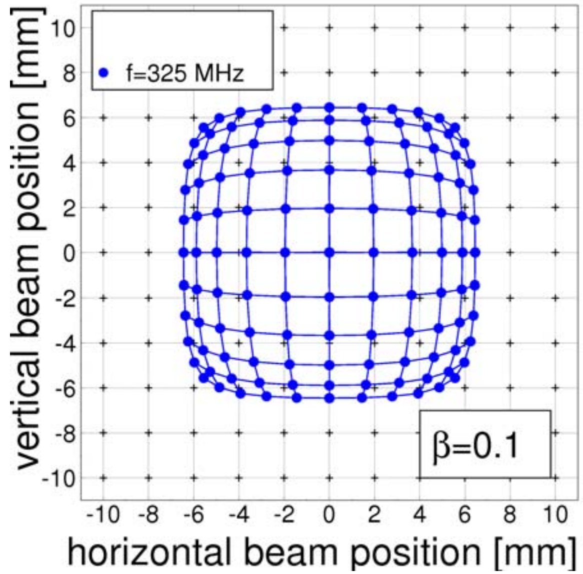
Sensitivity map for low β beam

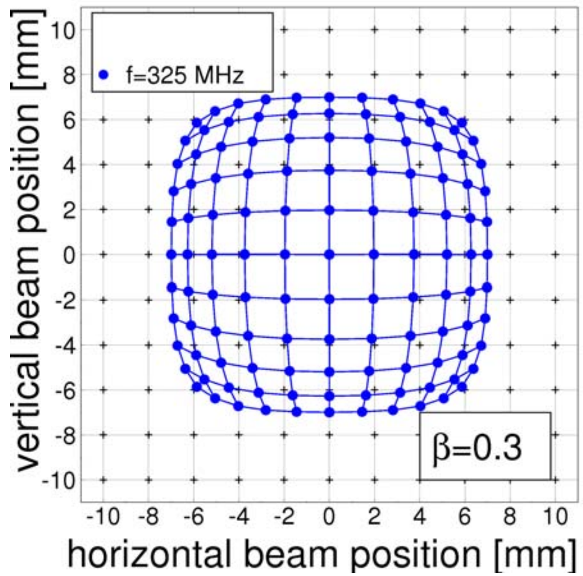
Parameters:

- ***BPM aperture: Ø 30 mm***
- f_{rf} ***= 325 MHz***
- ***bunch length*** σ_t ***= 150 ps***

Results:

- ***readouts are non-linear***
- ***xy-coupling***
- ***sensitivity map depends on***
  β and frequency (chosen rf harmonics)





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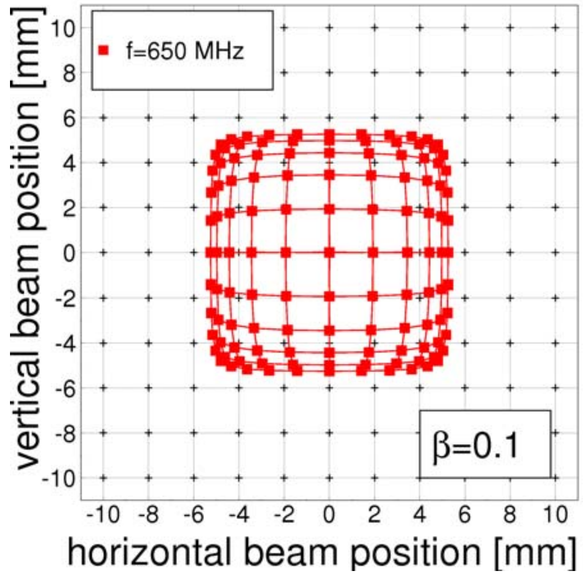

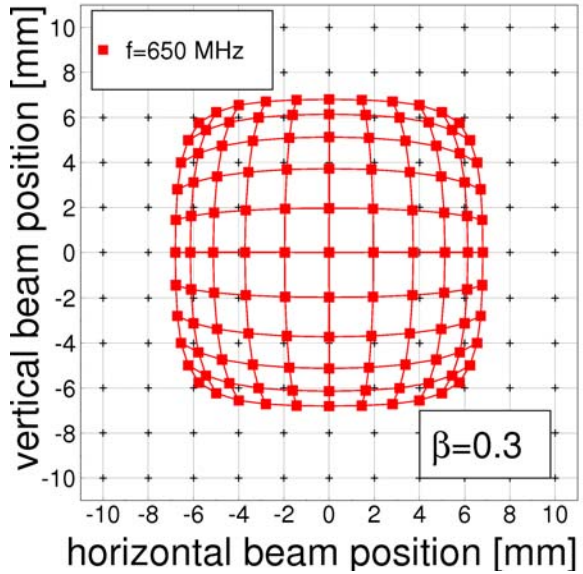

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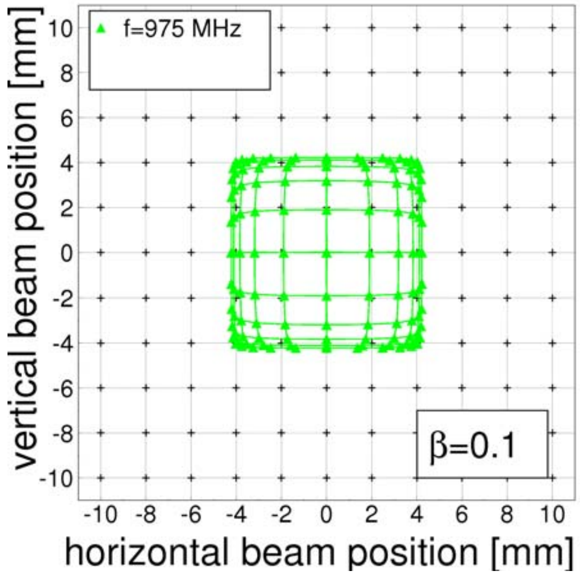

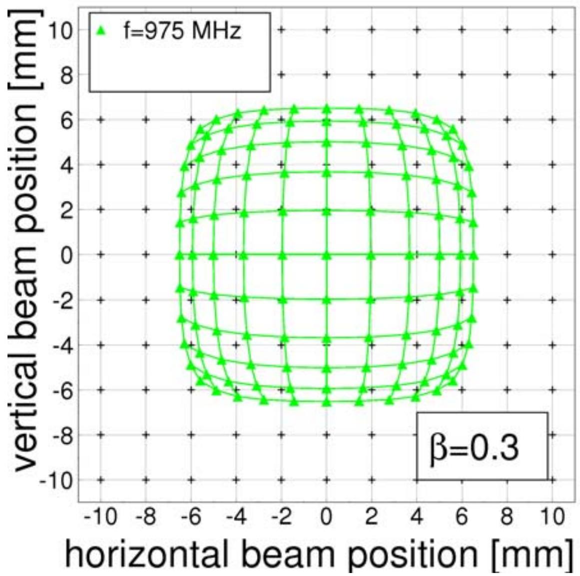

Sensitivity map for low β beam

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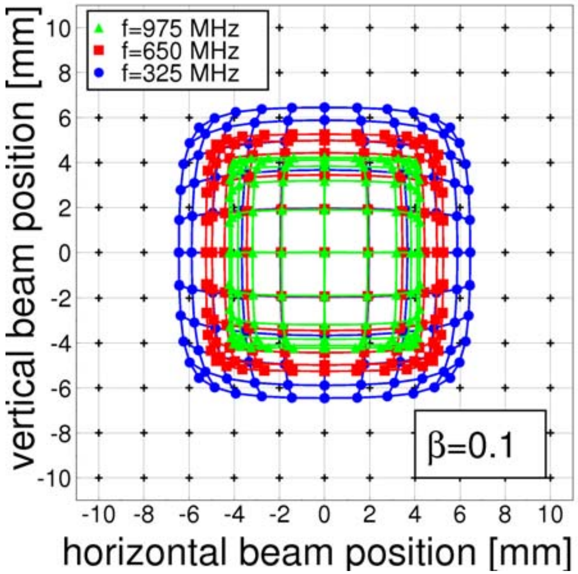
- *f_{rf} = 325 MHz*
- *bunch length σ_t = 150 ps*

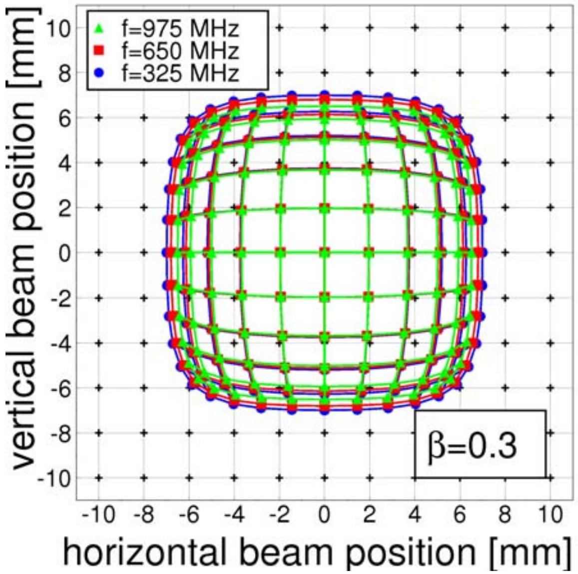
Results:

- *readouts are non-linear*
- *xy-coupling*
- *sensitivity map depends on*
  β and frequency (chosen rf harmonics)
  - *strong dependence for $\beta \leq 0.1$*
  - *weak dependence for $\beta \geq 0.3$*

Consequences:

- *sensitivity maps to be prepared for each location (β) and demand harmonics*
- *BPMs usable only for limited beam displacement:*
  (e.g. for β = 0.1 and 3 rd rf harmonics ±5 mm only i.e. ~30 % of aperture!)





Summary

FEM simulations are very helpful in BPM design since:

- ***check different approaches without prototyping***
- ***visualize fields propagation in BPM***
- ***allow to understand and control complex processes in BPM***
- ***the role of different BPM elements can be checked***
- ***optimize BPM position sensitivity***

Simulations are successfully used in the case of aspects that can not be investigated using “traditional methods” (e.g. low β beams).

Thank you for your attention

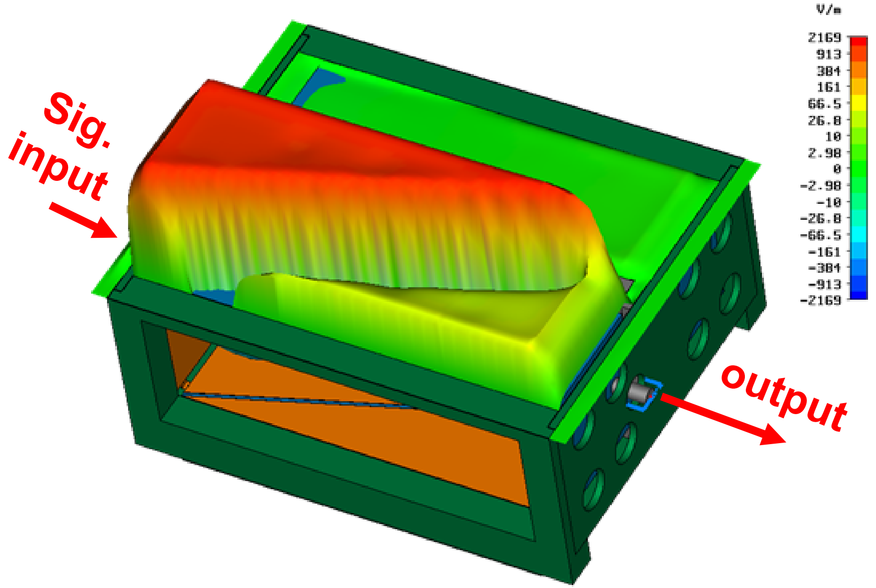
Thank you for your attention

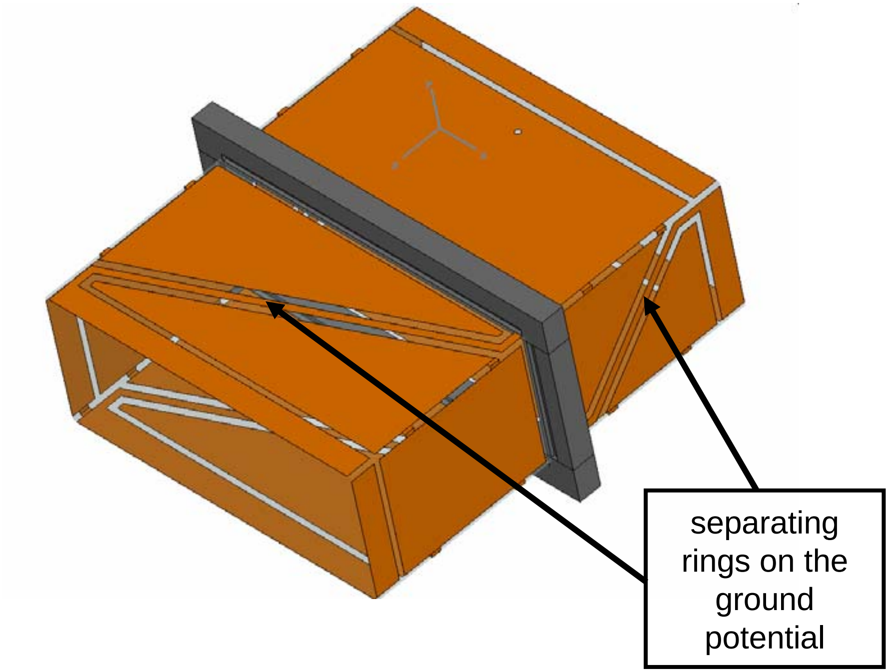
and patience ;)

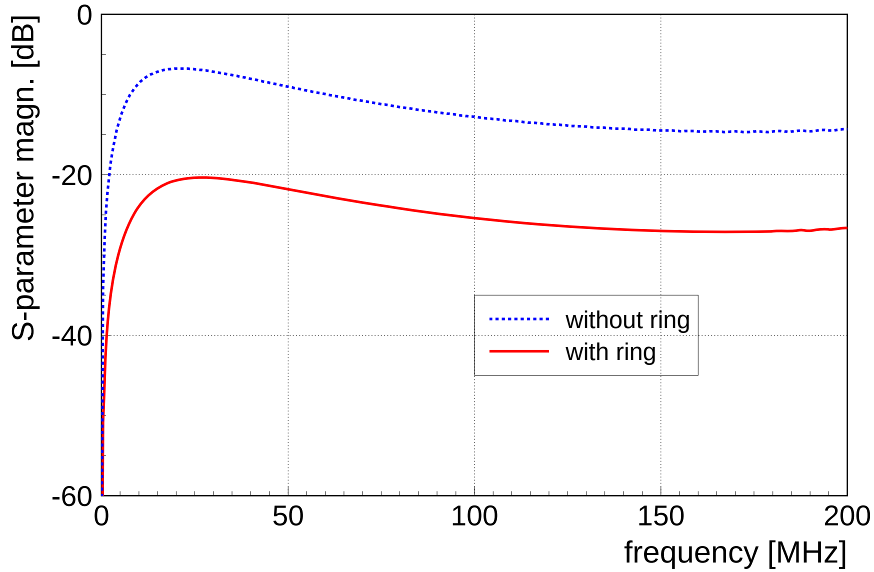
Backup transparencies

Reduction of the plate—to—plate cross talk

- ***Poor plate separation deteriorates position sensitivity***
- ***Plate—to—plate cross talk is caused by large ceramic permittivity ε=9.6 resulting in high coupling capacitance between adjacent plates***
- ***An insertion of the additional ring between adjacent plates reduces cross talks by more than 10dB***



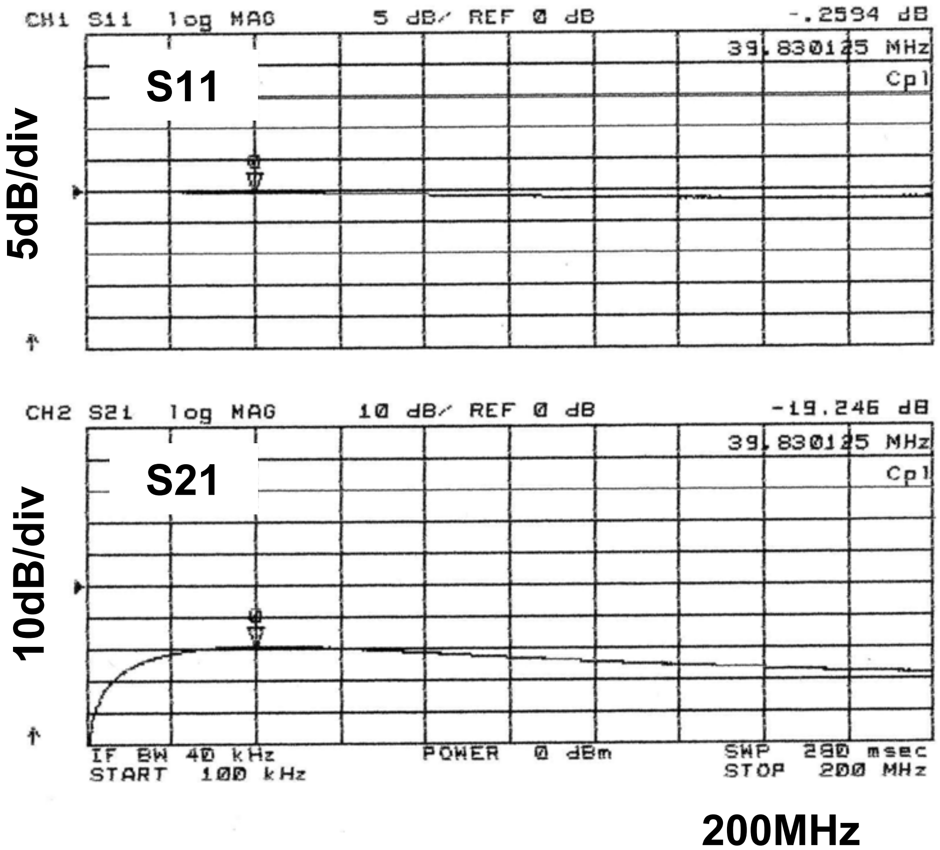




Measurements of the BPM prototype

BPM for HIT facility in Heidelberg (2005)

(NWA measurement)

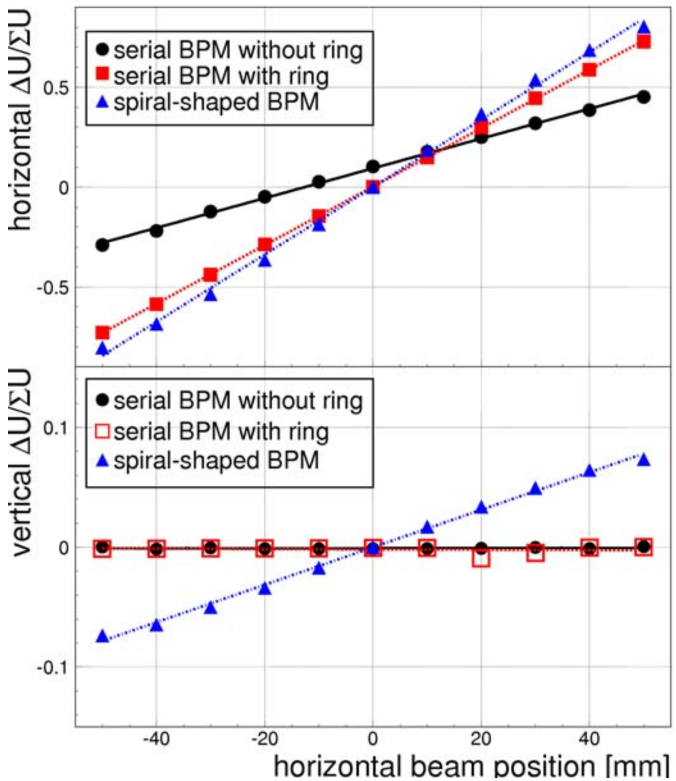


Other example: optimization for FAIR SIS-100

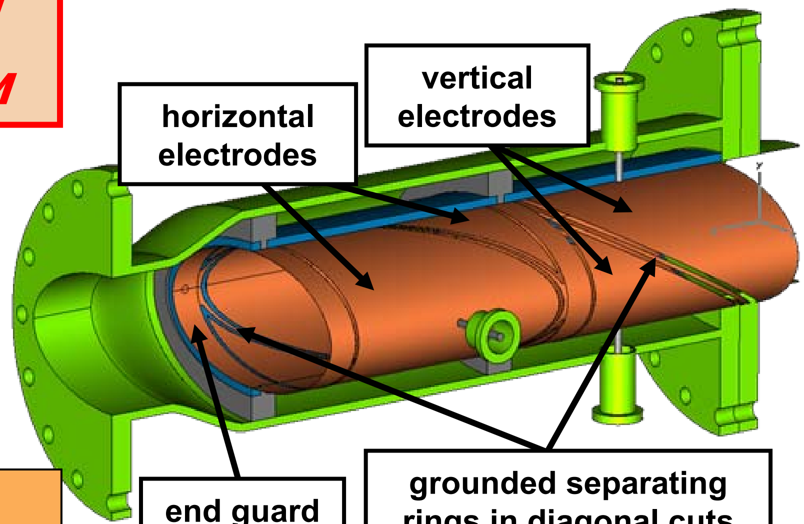
Three different geometries based on ceramic solution:

1. ***serial BPM before optimization***
2. ***optimized serial BPM with guard rings***
3. ***spiral shaped BPM***

(not optimal: hor.-ver. Coupling)

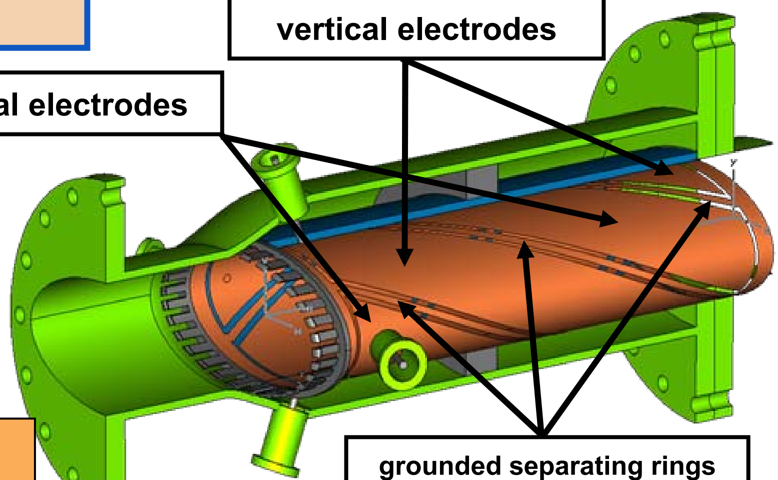


optimized serial BPM



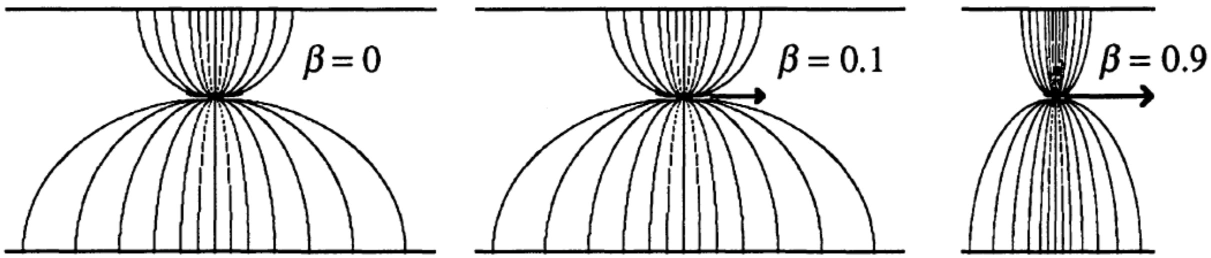
Aperture: 135x65 mm^2

spiral shaped BPM



Aperture: 135x65 mm^2

Low – Beta Beams (charge distribution)



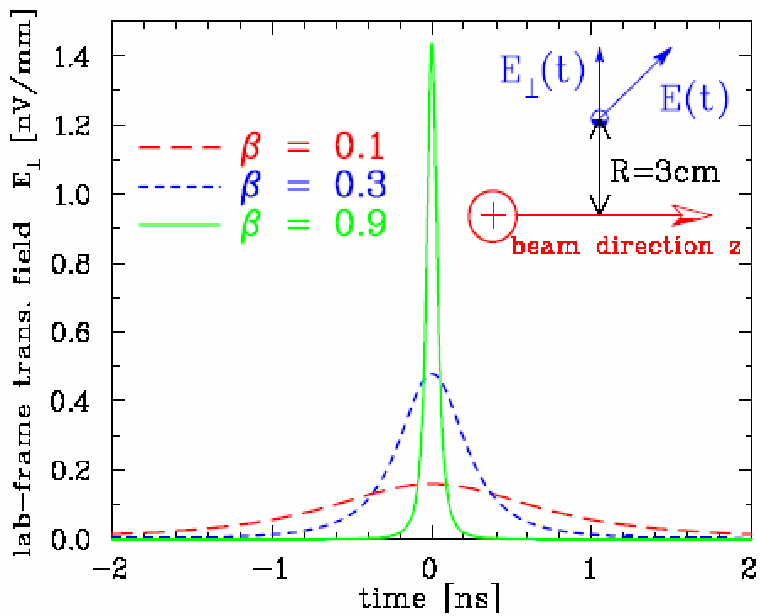
From R. Shafer, BIW 1993

E-field of a point-like charge:

$$E_\perp(t) = \frac{e}{4\pi\varepsilon_0} \cdot \frac{\gamma R}{\left[R^2 + (\gamma\beta ct)^2\right]^{3/2}}$$

E-field in lab coordinate system:

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

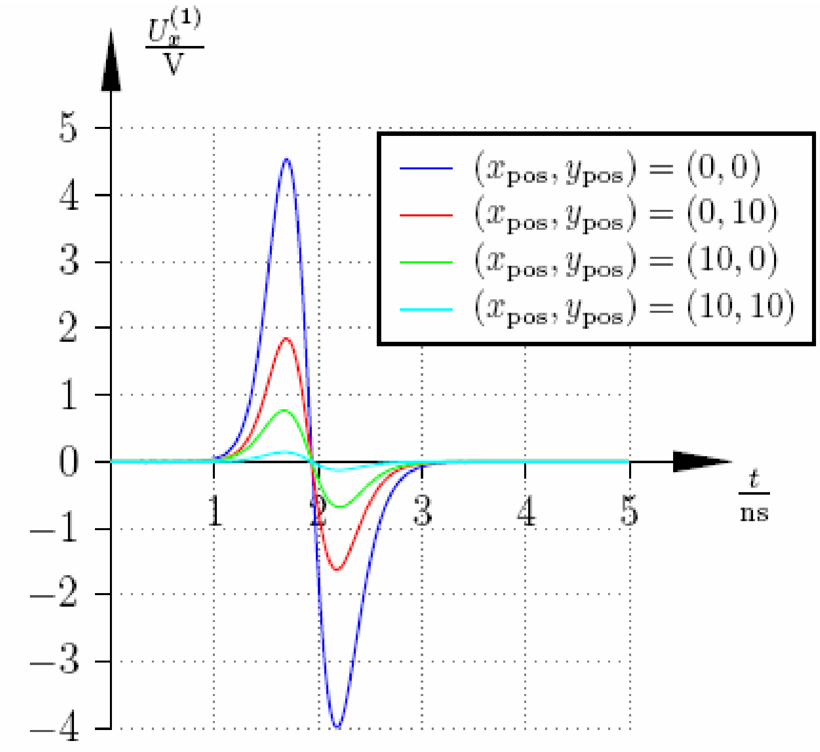


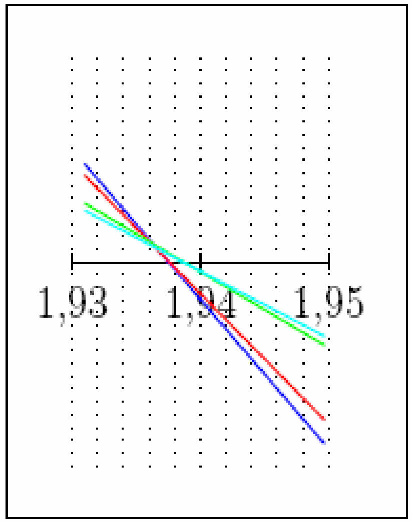
Time Evolution

- The pulse shape for β=20% with max. offsets of ±10 mm.
- Single plate signal ⇒ variation of zero crossing below 2 ps ≡0.2° !

⇒TOF measurement with oscilloscope possible

(but: sample rate of scopes < 10 GS/s)





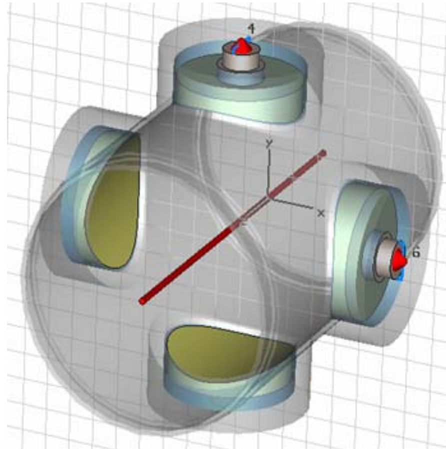
"Traditional" measurement of button BPM

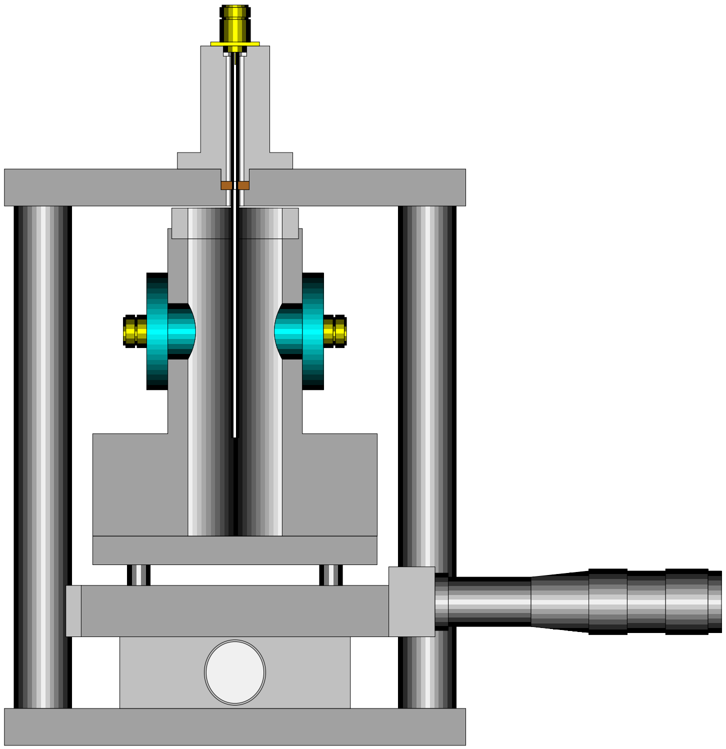
Measurement with movable wire antenna:

Results:

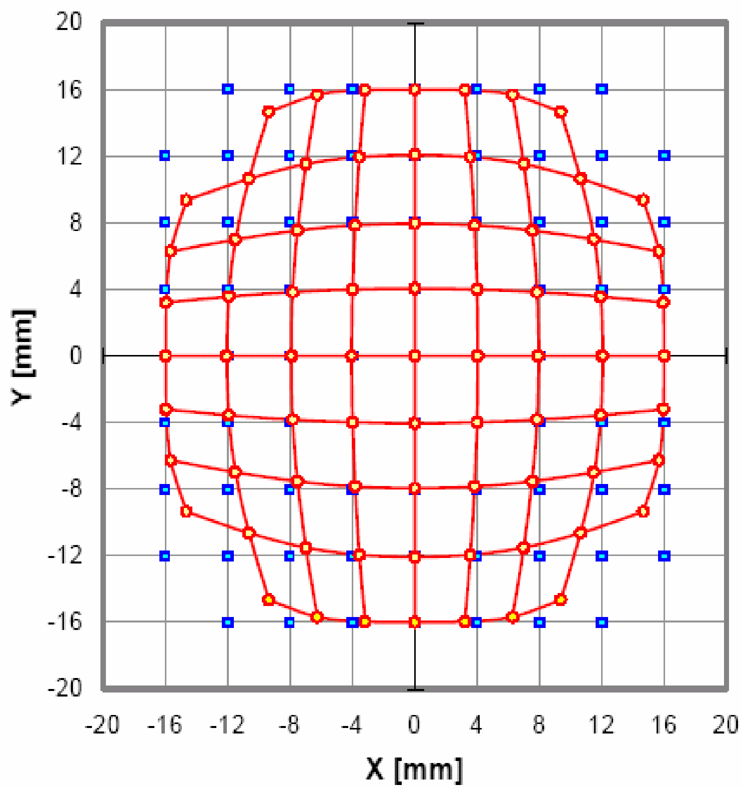
- *Non-linearity*
- *horizontal-vertical coupling*

$\Rightarrow$ *Polynomial fit with x and y dependence*



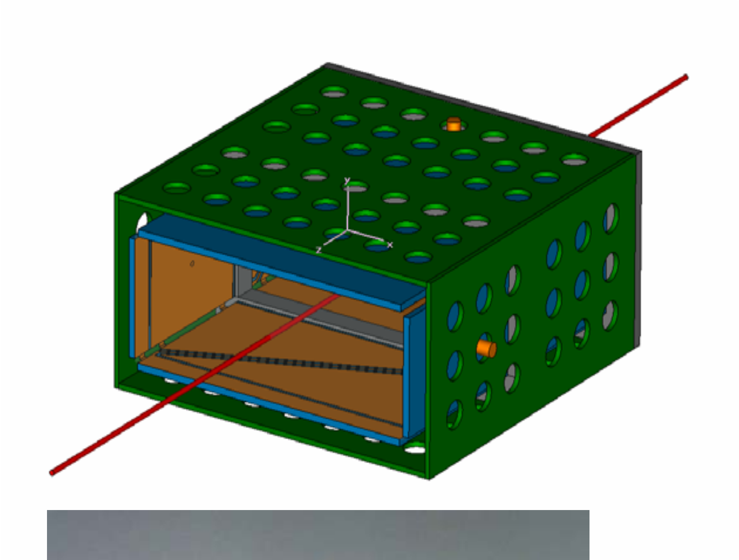


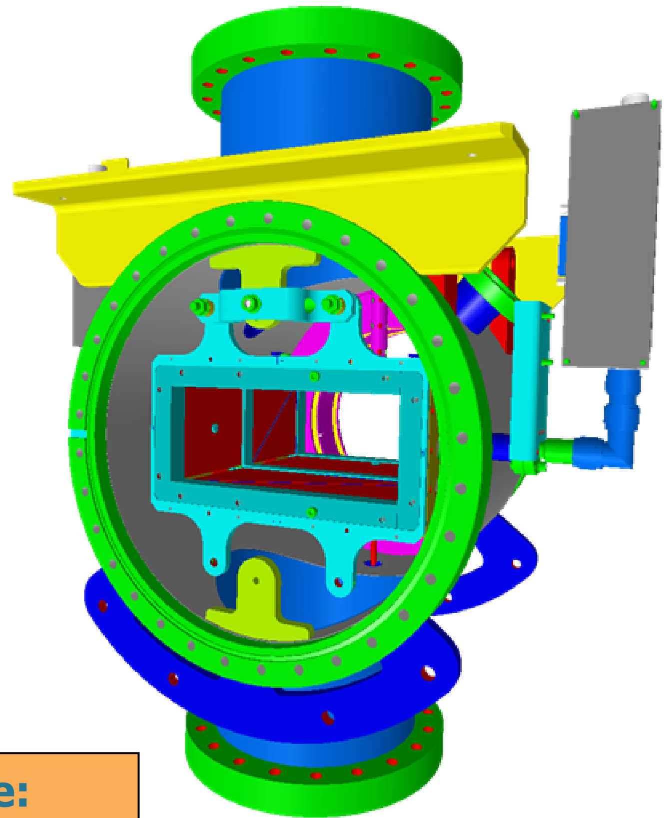
From C. Boccard et al. (CERN)



Example for technical realization

Technical realization for HIT synchrotron (design based on metal coated Al_2O_3 ceramic plates)





Aperture: 180x70 mm^2