BPMs from Design to Real Measurement.

Recipe for BPM system production for large number of items

> Introduction to BPMs
> Requirements
> Design with Simulations
> Prototyping and Measurements of Feedthroughs and Bodies
> Selection of Companies
> Series Production and Quality Tests
> Commissioning and Operation

Focused on mechanical aspects

Dirk Lipka, Silke Vilcins
5th International Particle Accelerator Conference
Dresden, Germany, June 15 – 20, 2014

Introduction to BPMs

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
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. wall current monitors, inductive antenna, BPMs with external resonator, slotted wave-guides for stochastic cooling etc.

P. Forck, CAS, Chios, Sep. 2011

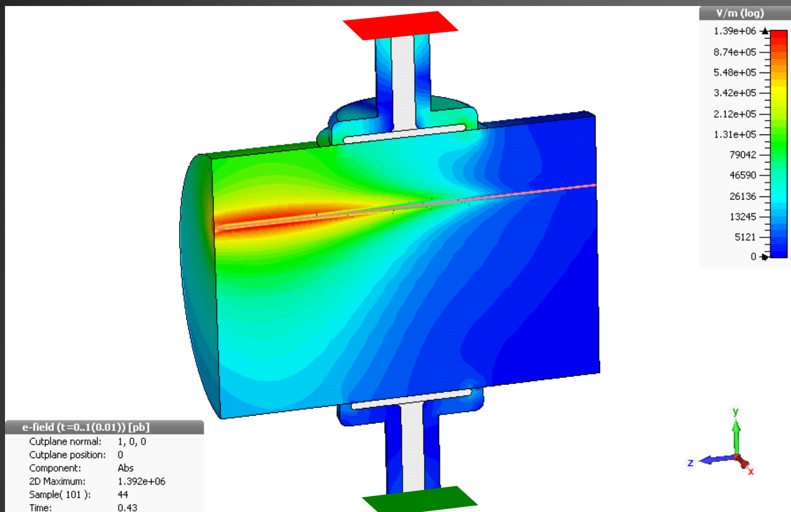
Courtesy P. Forck

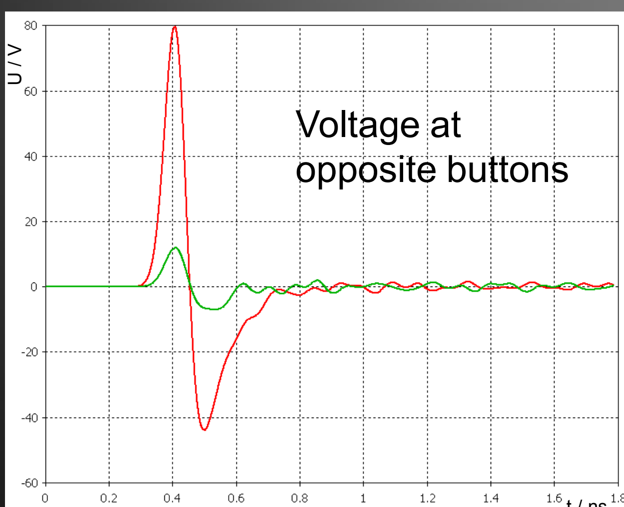
GSI

BPM: Principle and Signal Estimation

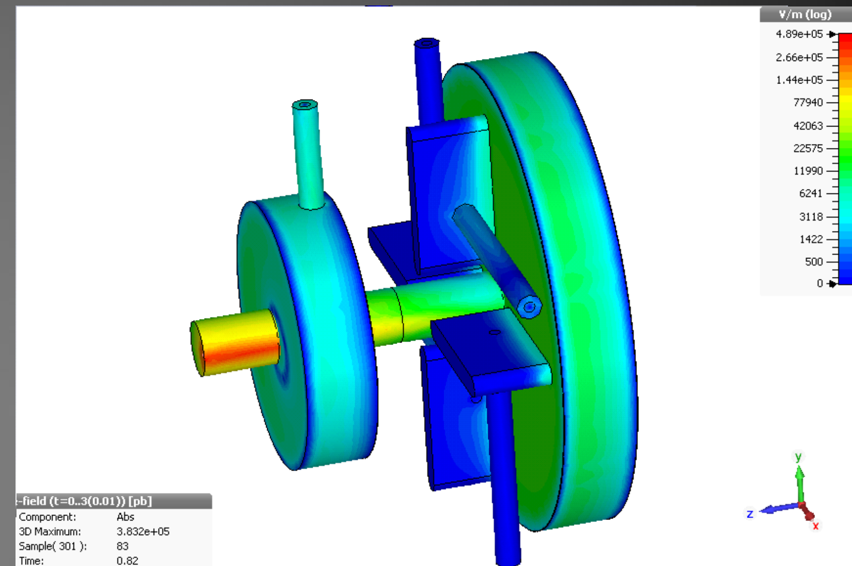
Introduction to BPMs

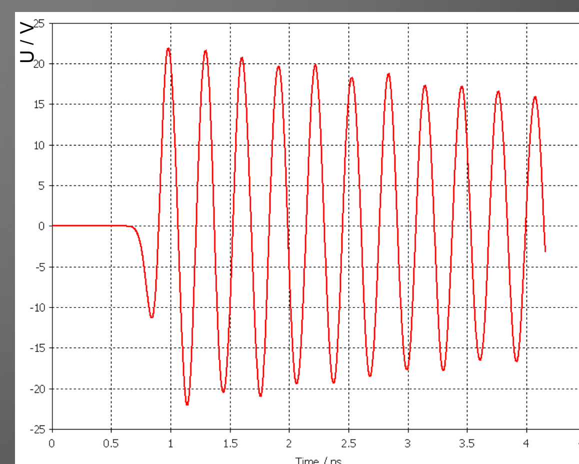
Button BPM simulation





Cavity BPM simulation





Voltage at
reference
resonator

Content

Requirements

Demand from machine to fulfill operation results in top level requirements (see P. Forck CAS 2008)

Requirements necessary for decision of BPM type:

- **Resolution** (relative position): influenced by type of BPM, electronics, ADC granularity …
- **Accuracy** (absolute position): influenced by mechanical tolerances, alignment accuracy, cable, support vibration, thermal effects …
- **Dynamic range:** beam current and transverse offset, for protons: energy range
- **Detection threshold:** minimum beam current for measurement
- Single- or multi-bunch detection
- Fast signal for machine protection
- Project budget and duration, availability of components, MTBF, maintenance and commissioning

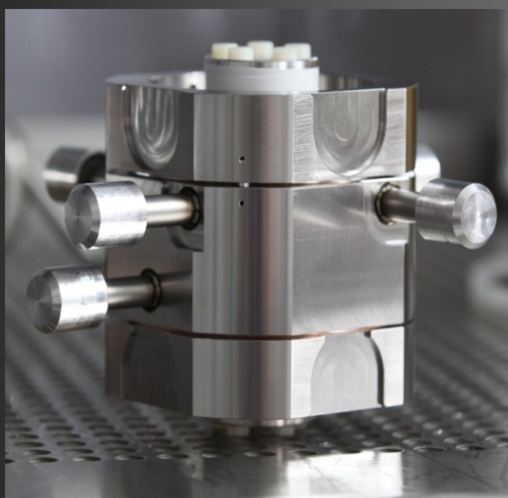
Requirements

Following boundary conditions have to be determined:

- Shape and sizes of beam tube (round, elliptical, rectangular …)
- Number of items
- Item space of the BPM
- Environment temperature: BPM at cryogenic temperatures?
- Area for BPM support (needs to be remotely moved for calibration?), vibrations
- Vacuum aspects like pressure or particle reduced area
- Distance between BPM and front-end electronics (attenuation of signal amplitude, phase synchronization)
- Area for electronics (within the accelerator room: shielding, EMC aspects; temperature stability at rack)
- Sub-components: trigger (extern/intern), synchronization, server, …
- Low maintenance effort

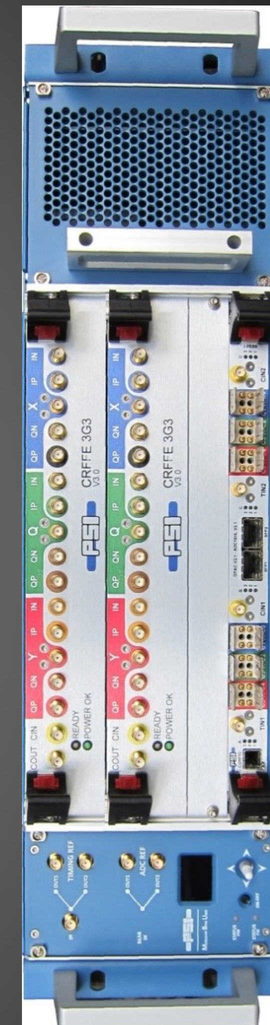
Requirements

Between BPM mechanics and front-end electronics following values have to be agreed:



European XFEL cavity BPM, photo D. Nölle

- **Sensitivity:** factor between position and signal quantity (e.g. Δ/Σ, $\log(U_1/U_2)$, amplitude etc.)
- **Bandwidth:** frequency range available for measurement including deviations due to production
- **Signal to noise:** ratio between wanted and unwanted background amplitude



Modular BPM unit with cavity BPM front-ends for European XFEL provided by PSI

These values have to be chosen to comply the top level requirements

Calculate expected system performance

Content

Design with Simulations

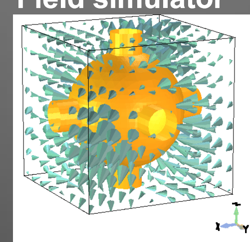
BPM system: **mechanics** and **electronics**. The way to develop the system:

- Either prototype based on analytic expressions, measure properties in the laboratory and accelerator, optimize the design, repeat prototyping and afterwards develop the electronics; very time consuming.
- Or predict properties of the basic BPM design with analytical expressions followed by simulations. This as input for the electronics development in parallel to the BPM development (time saving).

Therefore: use Simulation tool for the prediction of BPM performance, e.g. CST, HFSS, GdfidL, COMSOL, ACE3P etc. (This list does not claim to be exhaustive.), because complete design structure can be taken into account without approximation (regards the simulation resolution)

CST

The GdfidL Electromagnetic Field simulator



COMSOL

ACE3P (Advanced Computational Electromagnetics 3D Parallel) Code Suite

SLAC

...

DESY

Design with Simulations

Estimated duration of BPM system development from the design to commissioning including simulations

	Button	Stripline	Cavity
Development (mechanics + electronics)	1 – 2 years	2 – 2.5 years	3 – 4 years
Industrialization	1 – 2 years	2 years	2 years
Series production (>100 items) including vacuum components, supports, electronics	1.5 – 2 years	2 years	2 – 2.5 years
Firmware and server		0.5 year	
Commissioning	0.5 year	0.75 year	0.5 year

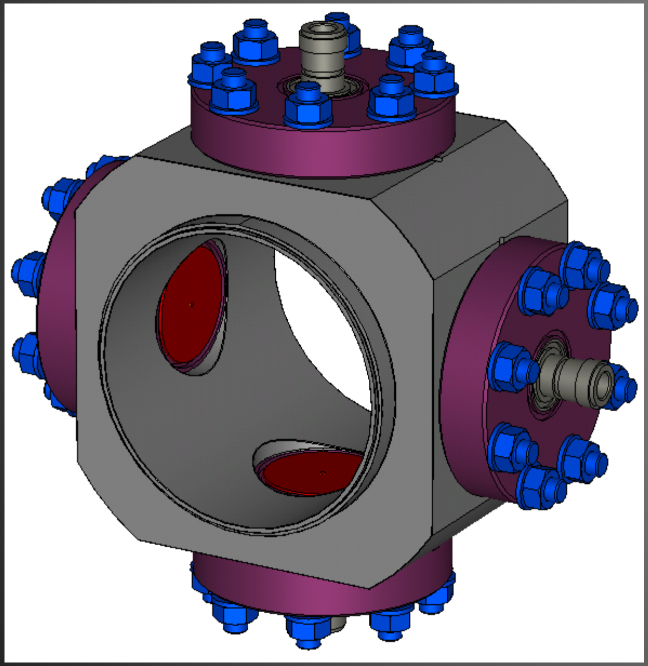
Total time is shorter as sum because they overlap to each other; development time based on design of existing predecessor version

Duration comparable to accelerator development time: BPM separate project, start in an early stage of the accelerator development

Design with Simulations

BPM effectively simulation: mechanical design reduction to RF design (reduction number of simulation mesh cells and therefore decrease the simulation time)

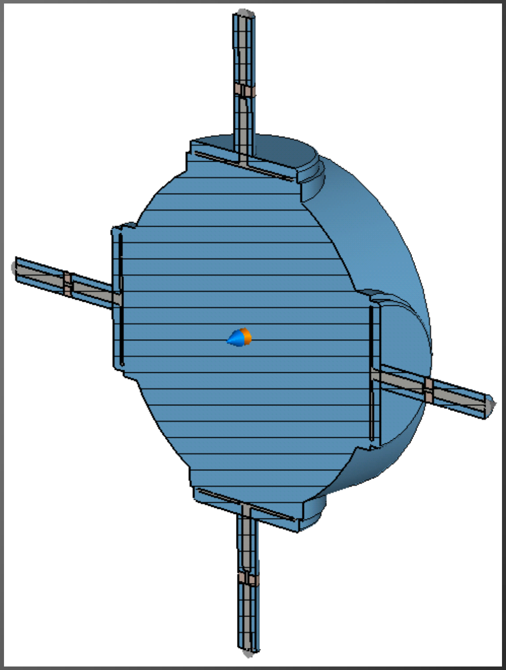
Button BPM design for the European Spallation Source (ESS)



Reduction of design to the vacuum part with button and feedthrough

Finished RF design conversion to mechanical design

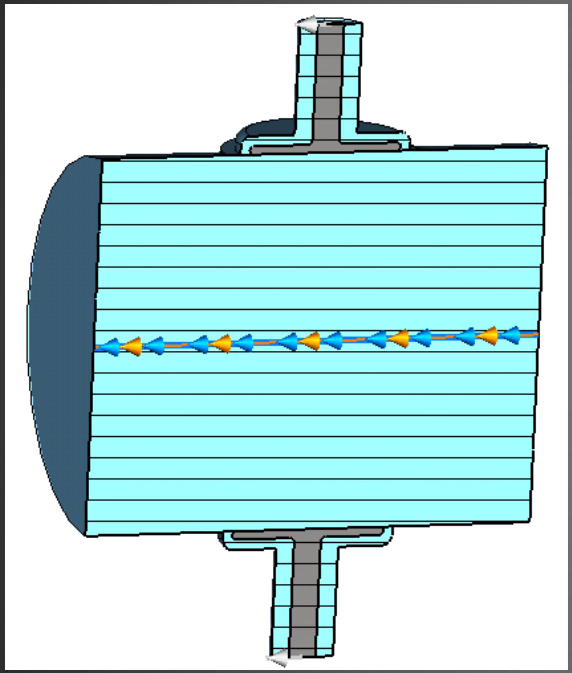
RF equivalent geometrical simulation model (cut view)

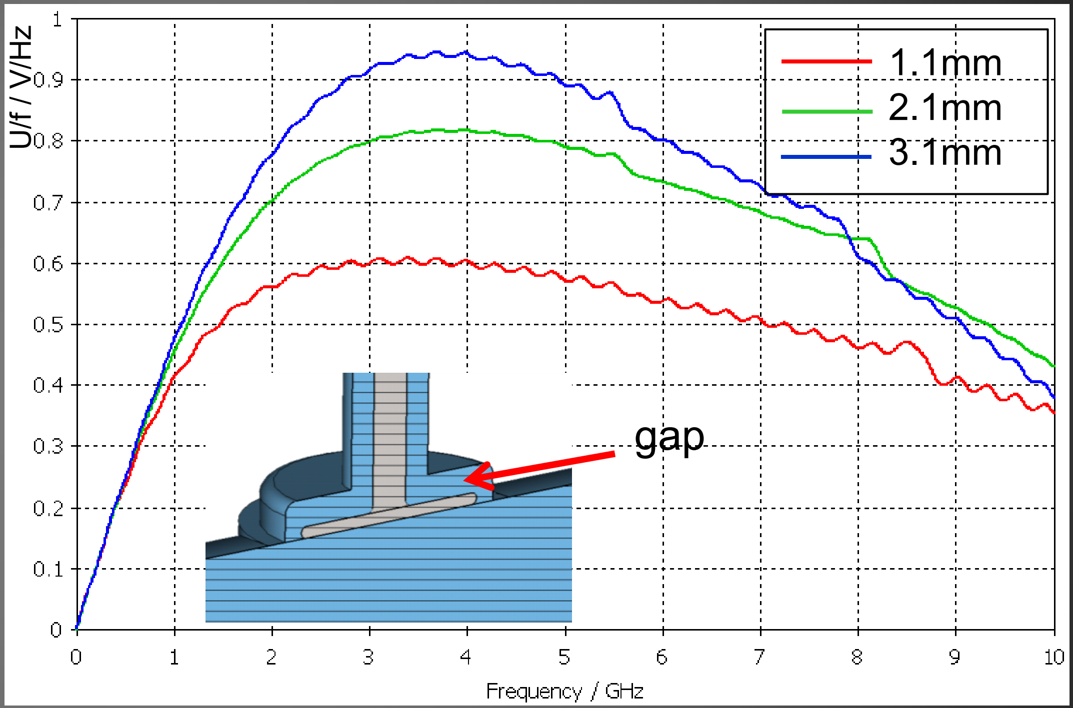


Design with Simulations: Signal Optimization

Start with analytic solution results in raw design

- Optimization with simulation (attention to resolution of simulation with respect to system requirements)

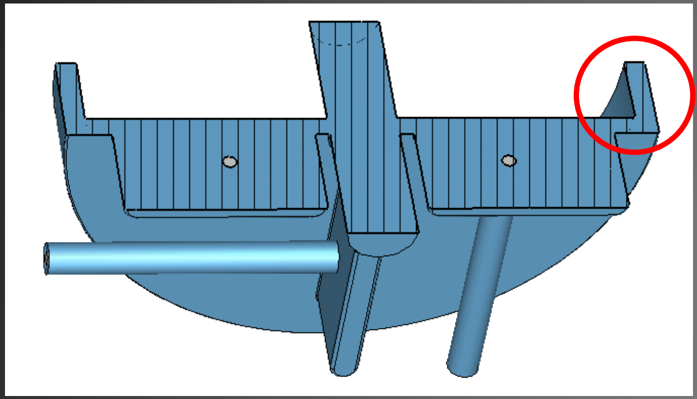


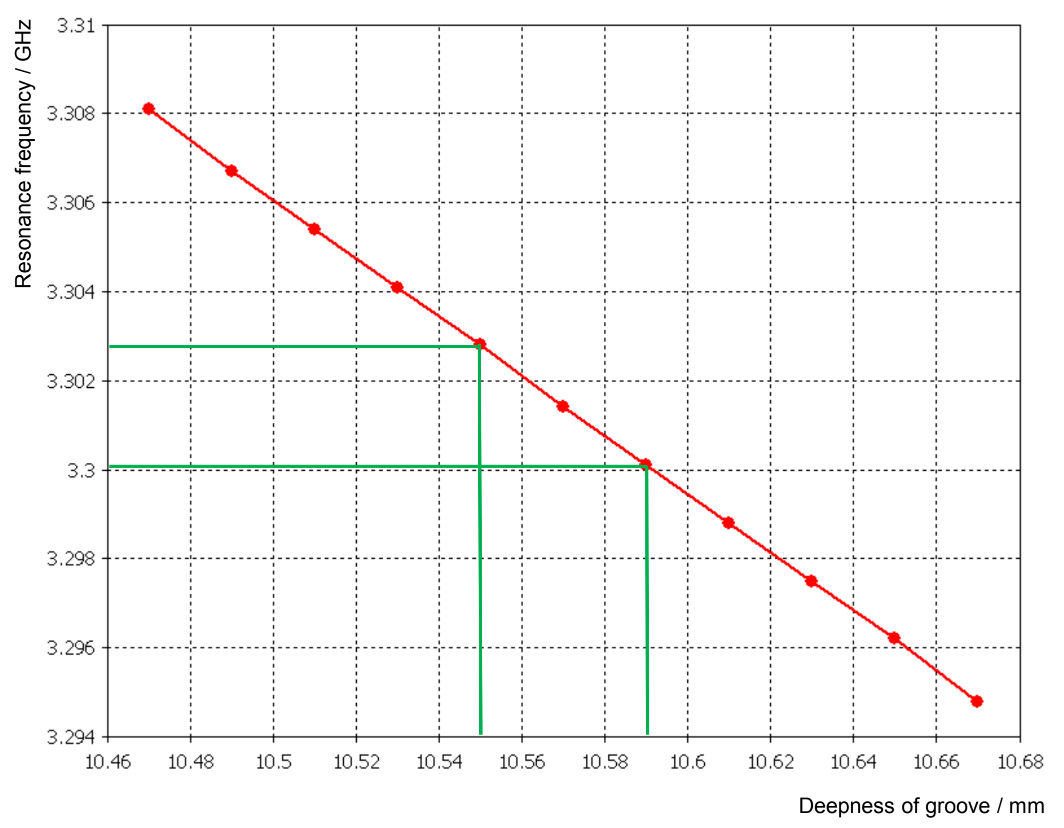


- Example: European XFEL button BPM with different gap distances behind button
- Results: between 1 and 9 GHz higher amplitude without resonances

Design with Simulations: Tolerance Studies

Example: cavity BPM

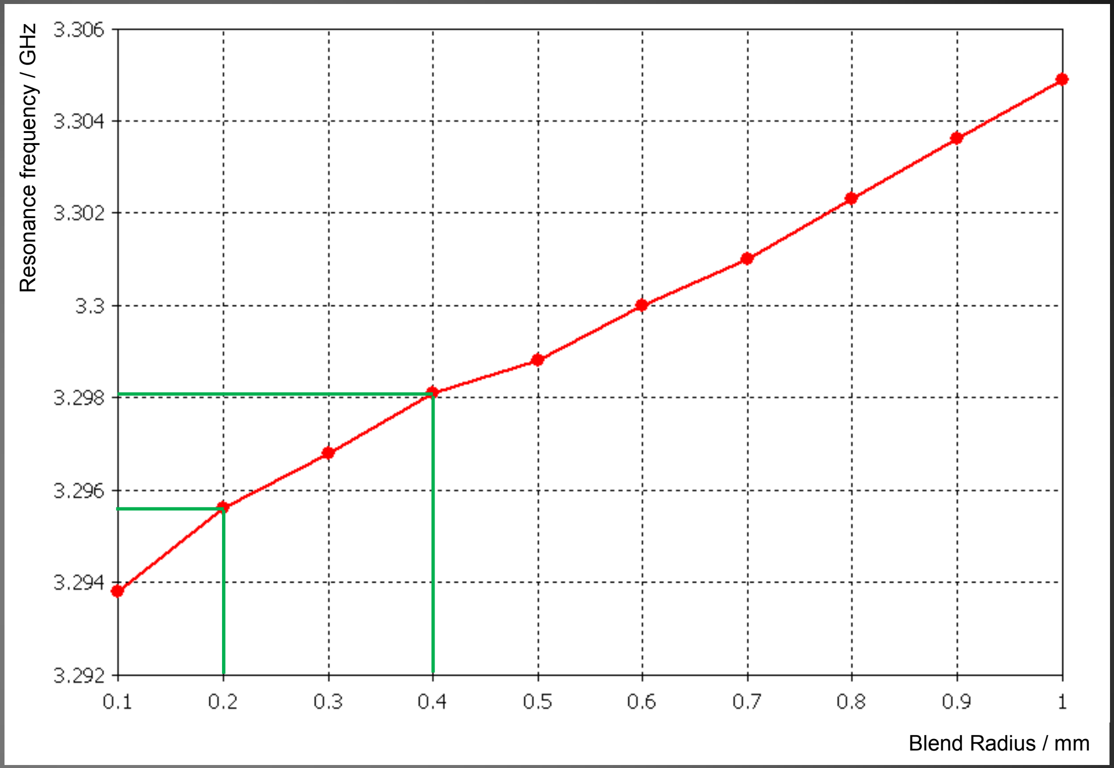


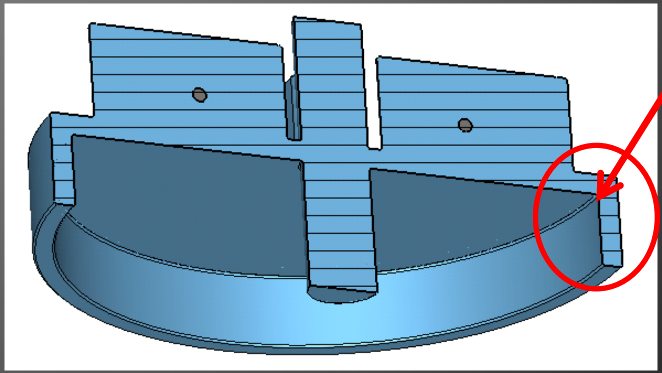


- Investigation of signal influence due to tolerance
- Result: bandwidth of the electronics defines the **mechanical tolerance**
- **Interplay**: electronics capability ⟷ simulation ⟷ mechanical feasibility
- Reduction of BPM system price with looser tolerance due to electronics capability

Design with Simulations: Tolerance Studies

- This example: cavity BPM with different blend radius between resonator and groove
- Investigation for each mechanical value to define the tolerances for the production
- Sum of all mechanical tolerances results in worst case of bandwidth range or simulate all correlations when number of parameters small enough
- Time consuming but necessary for the mechanical design





Design with Simulations: Dissipated Power

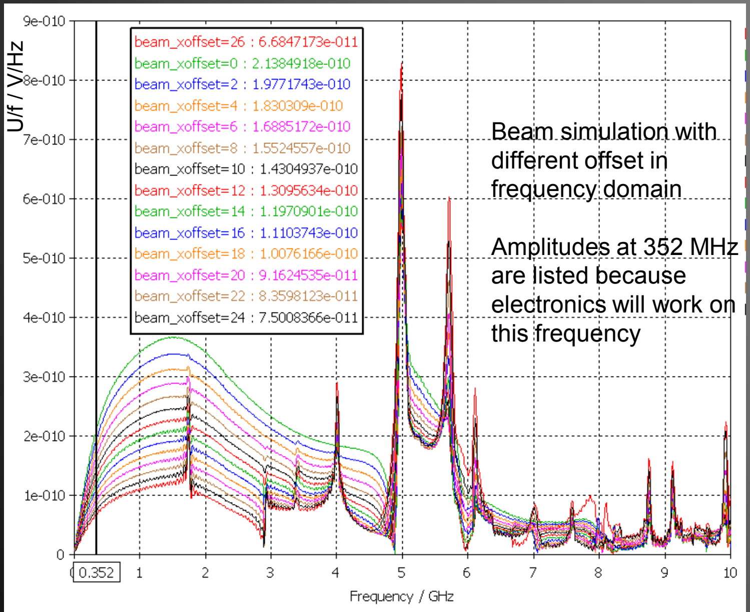
Simulation: dissipated power and temperature

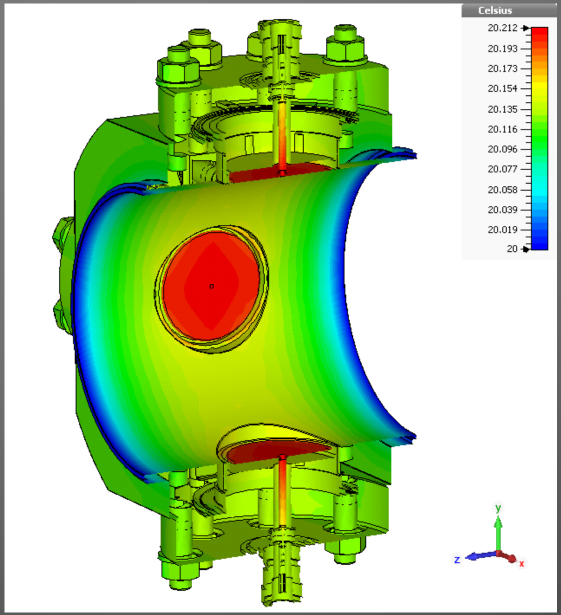
- Example: button BPM for ESS

Observed strong resonance above 5 GHz

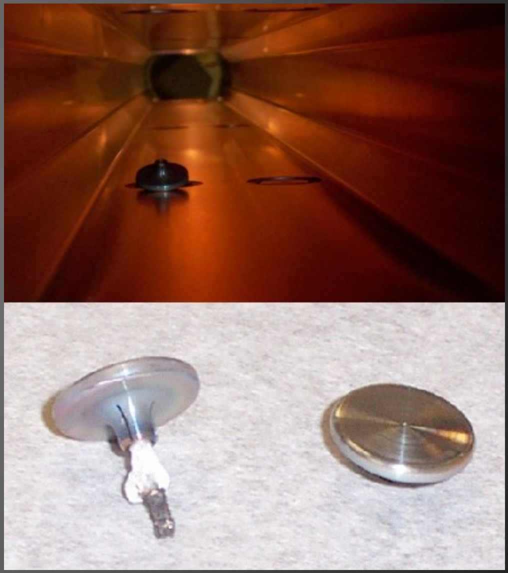
- Simulation of wake loss and Eigenmode as input for thermal (attention to thermal boundary conditions, conductivity and radiation)

Result: only negligible temperature rise





Do not observe this in your machine (not ESS)

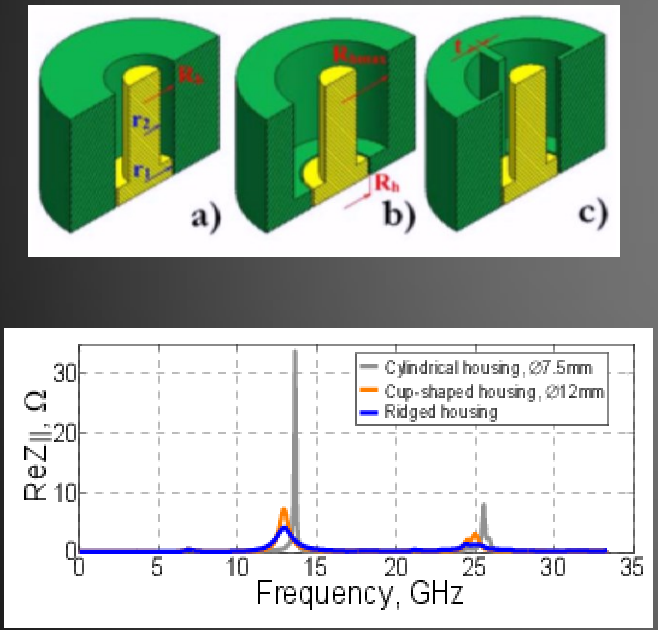


Photos taken from A. Novokhatski

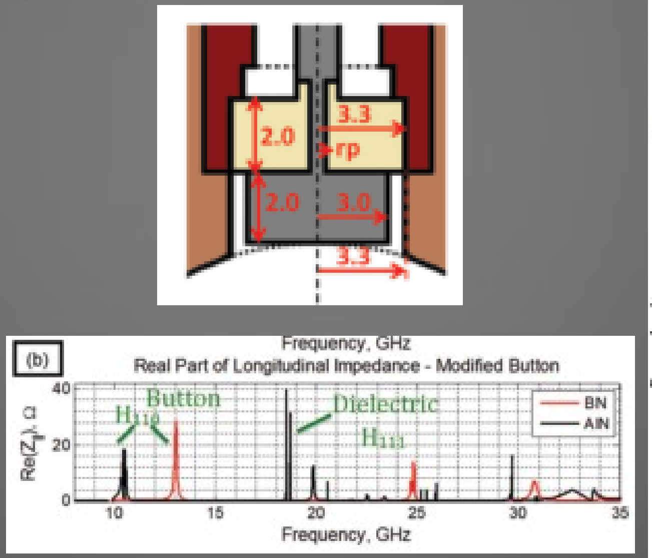
Design with Simulations: Button Resonances

Special care induced heat dissipated to antenna and feedthroughs with trapped mode, some examples are shown here

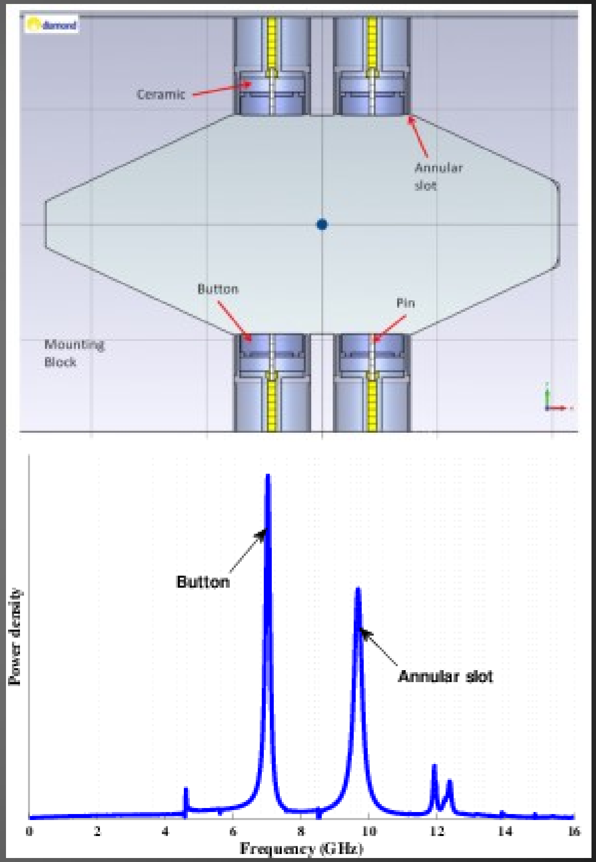
- These considerations are essential for high current machines and should be integrated into the basic simulation considerations



Ref.: A. Blednykh et al., design button BPM for the NSLS-II ring



Ref.: H. O. C. Duarte et al., design button BPM for SIRIUS storage ring



Ref.: A. F. D. Morgan et al., button BPM at the Diamond storage ring

Design with Simulations

Dissipated power important for high duty cycle machine with high current

List to avoid RF heating (not only BPMs)

BEAM-INDUCED RF HEATING (13/14)

- Usual solutions to avoid RF heating => Depending on the situation
  - Increase the distance between the beam and the equipment
  - Coat with a good conductor (if resistive losses and not geom.)
  - Close large volumes (could lead to resonances at low frequency) and add a smooth transition => Beam screens, RF fingers etc.
  - Put some ferrite with high Curie temperature and good vacuum properties (close to maximum of magnetic field of the mode and not seen directly by the beam) or other damping materials (AlN-SiC Ceralloy 13740Y as in PEP-II)
    - Power loss can be significantly decreased
    - The ferrite should absorb the remaining (much smaller) power => Still potential issue of heating due to bad contact / conduction
  - Increase the bunch length (if possible). The longitudinal distribution can also play a very important role for some devices, and it should be kept under tight control

Elias Métral, IBIC 2013, Oxford, 16-19/09/2013 16/31

BEAM-INDUCED RF HEATING (14/14)

- Improve the subsequent heat transfer
  - Convection: none in vacuum
  - Radiation: usually, temperature already quite high for radiation to be efficient. One should therefore try and improve the emissivities of surrounding materials
  - Conduction: good contact and thermal conductivity needed
  - Active cooling: LHC strategy was to water cool all the near beam equipment
- Try and design an All Modes Damper (AMD) if possible, to remove the heat as much as possible to an external load outside vacuum, where it can be more easily cooled away. This can also work together with a damping ferrite
- Install temperature monitoring on critical devices to avoid possible damages

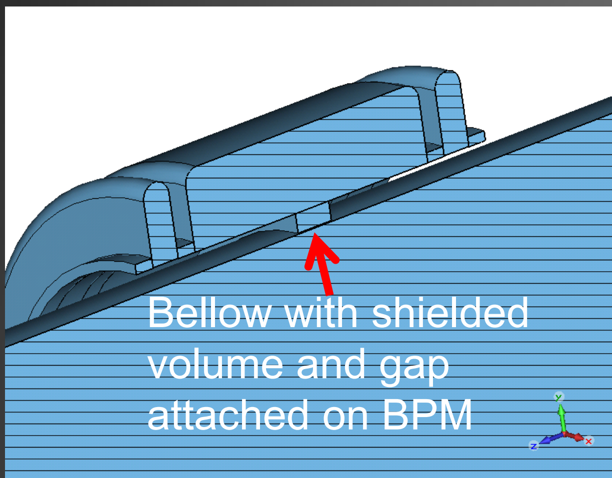
Elias Métral, IBIC 2013, Oxford, 16-19/09/2013 17/31

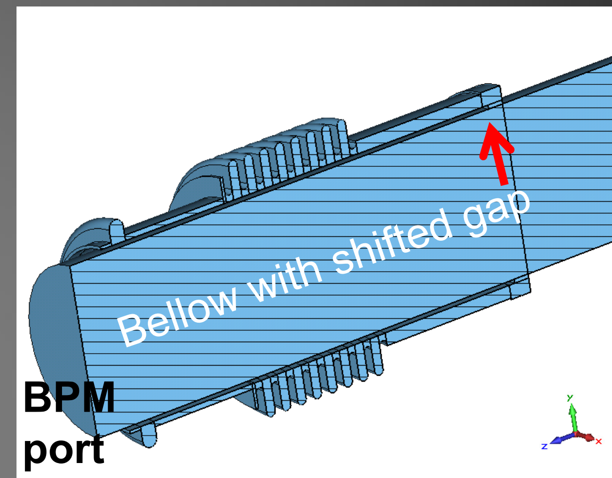
Summary mini-workshop RF heating at Diamond Jan. 30, 2013, courtesy E. Metral

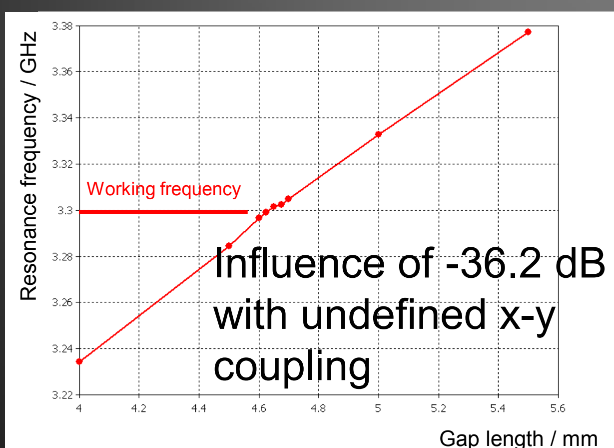
Ref.: http://www.diamond.ac.uk/Home/Events/2013/Simulation-of-Power-Dissipation---Heating-from-Wake-Losses.html

Design with Simulations: Watch your Neighbors

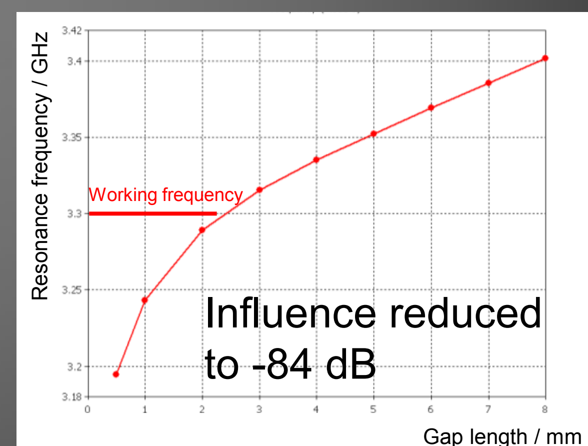
Influence of nearby components







Larger distance between BPM resonator and bellow gap



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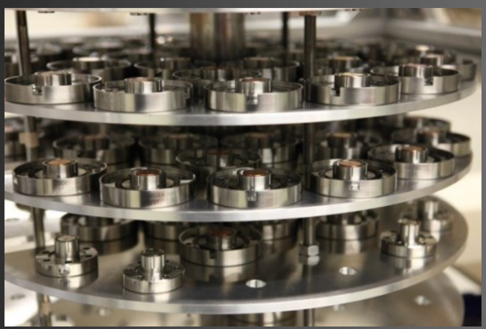
Prototyping and Measurements: Feedthrough

Special care to feedhroughs, e.g. Buttons in cryogenic chamber

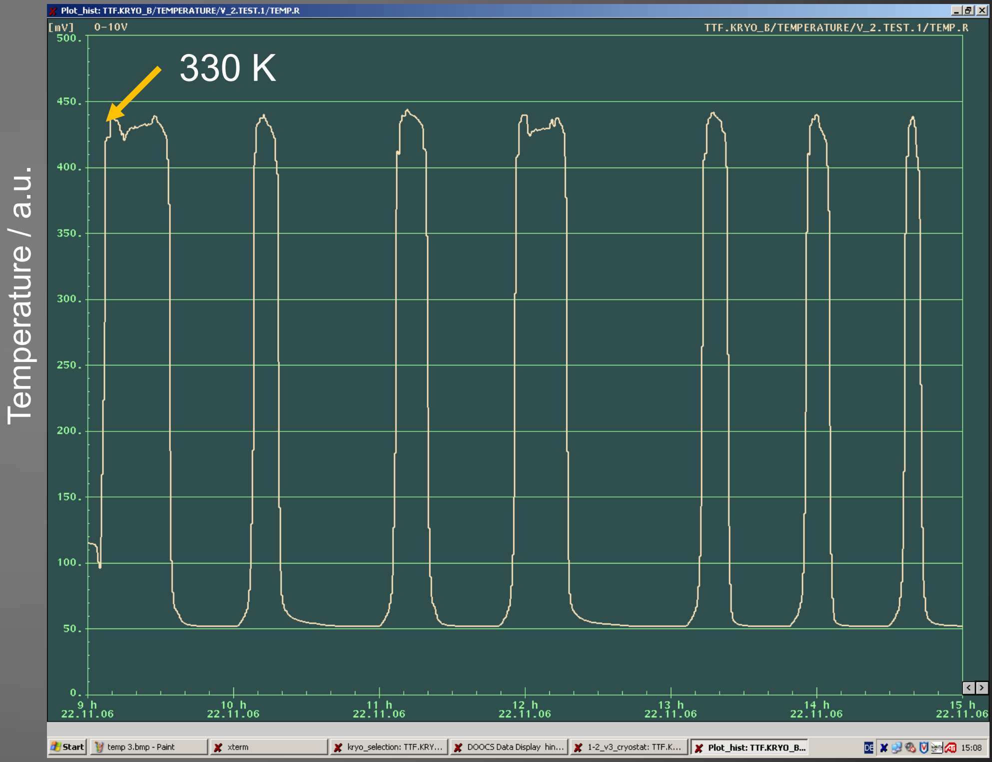
Cryogenic tests of all feedthroughs (10 cycle of 90 parts pre series and 3 cycle term of series production)



Setup with several button BPM feedthrough to insert them into the cryostat

Measurement between 330 K and 4.5 K liquid helium, 10 cycles (7 shown)

Leak check during test cycles show if there is a broken feedthrough or a leak gasket

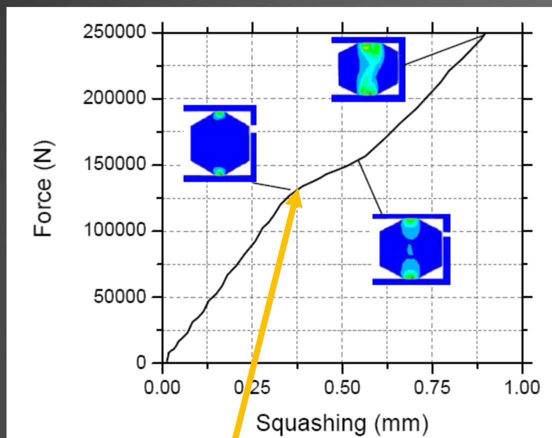


Result: all 90 pre series items passed these tests

Prototyping and Measurements: Feedthrough

Gasket + electrical offset

Force vs. deformation of Aluminum gasket



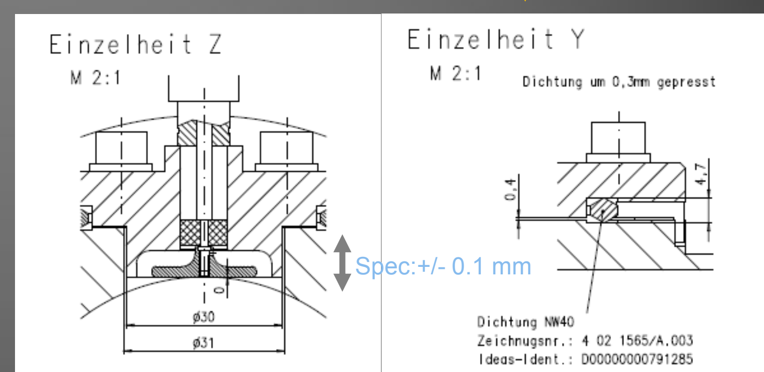
Point 0.375 mm!

Photo of „diamond“ formed gasket with cold feedthrough prototype; provided by S. Vilcins

Safe and reliable contact between body, gasket and feedthrough

Gasket has to be pressed by 0.3 mm to be within elastic region

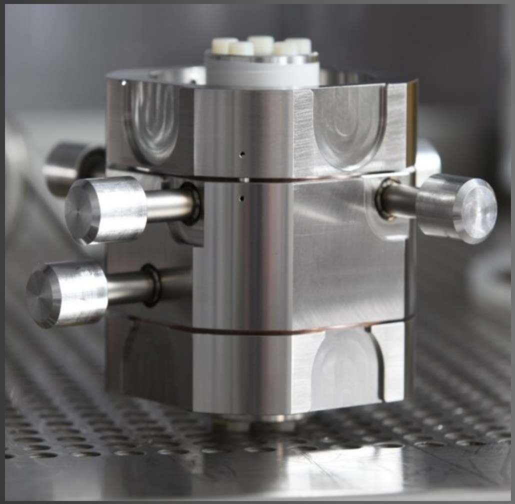
Simulation tolerance: plus 0.1 mm maximum for the button deepness tolerance



Prototyping and Measurements: Feedthrough

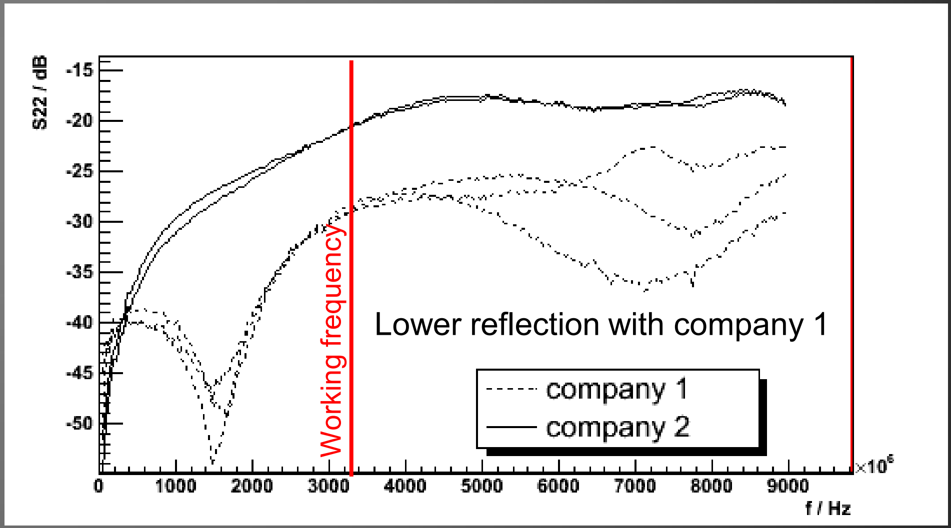
Feedthrough influence to external Q due to higher reflection

- Observed quality factor change by 30%; unfortunately at different signs for both resonators



European XFEL cavity BPM, photo D. Nölle

Measurement adapter for matching resonator side with a network analyzer to measure reflection



<u>Therefore: influence of feedthrough to the BPM signal has to be observed before the design is finished</u>

Prototyping and Measurements: Feedthrough

- Feedthroughs with Button produced in companies
- If the requested design not available: develop new design
- Example: Button BPM for European XFEL with feedthrough

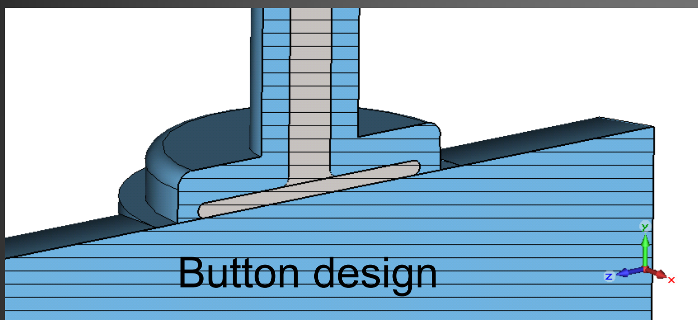
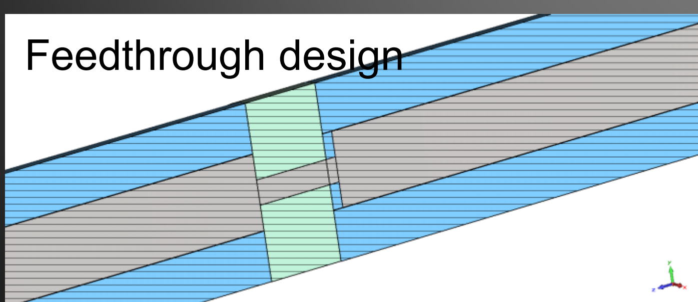
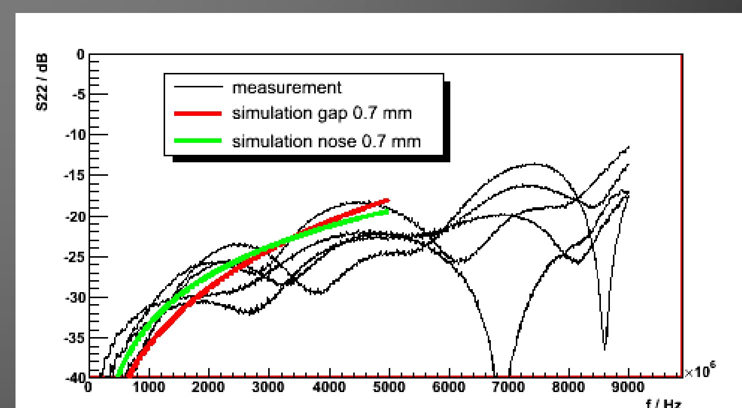


Photo:
D. Nölle

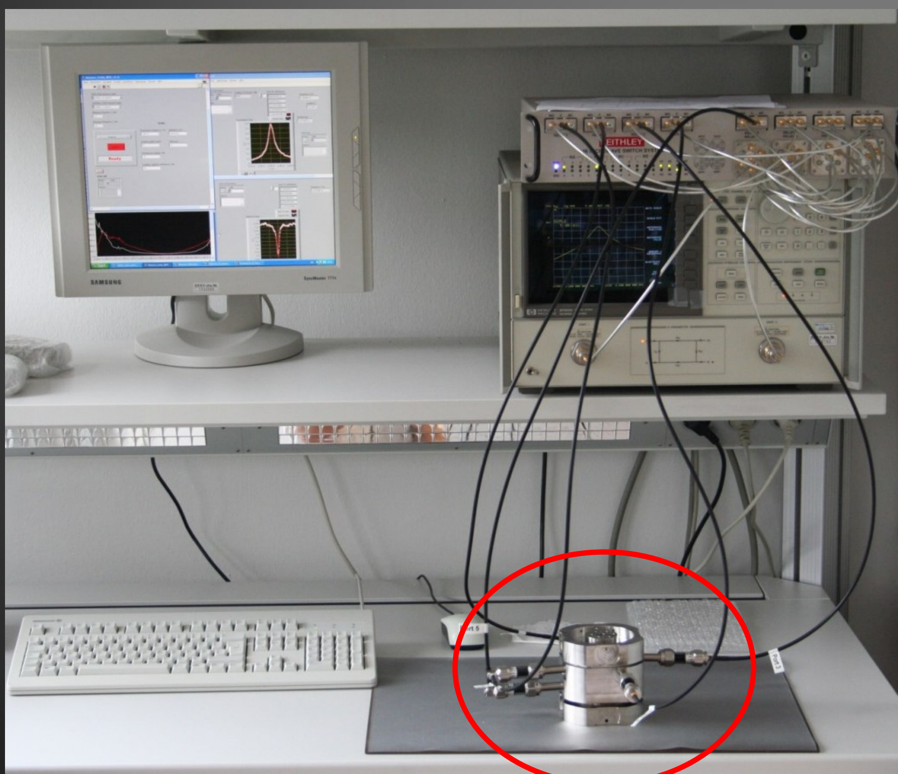
Realization of the design

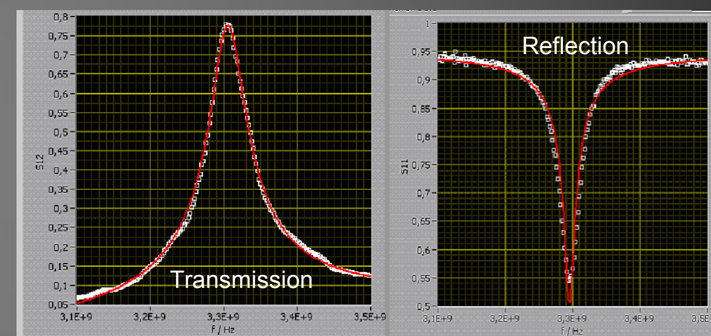


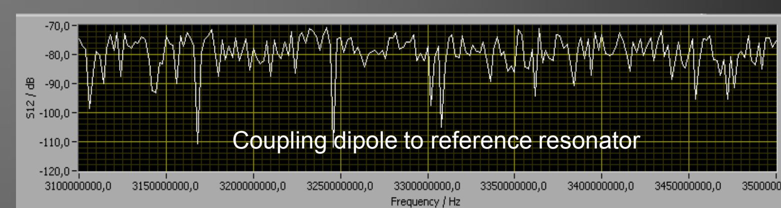


Prototyping and Measurements: Body

- Production prototypes in-house (familiar with small numbers of items)
- Test setup development and commissioning for series quality test



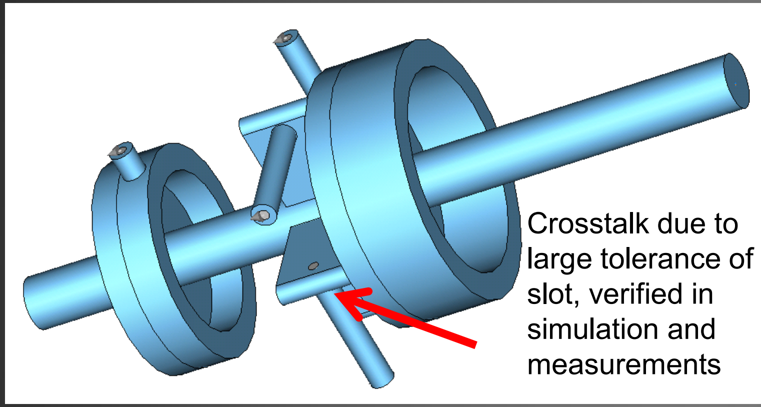


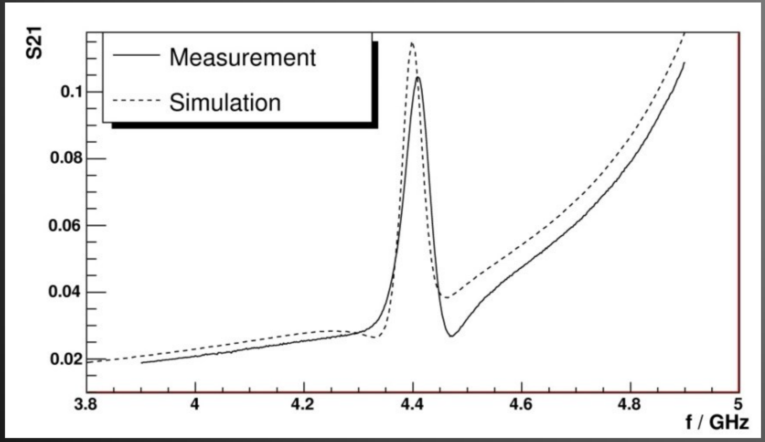


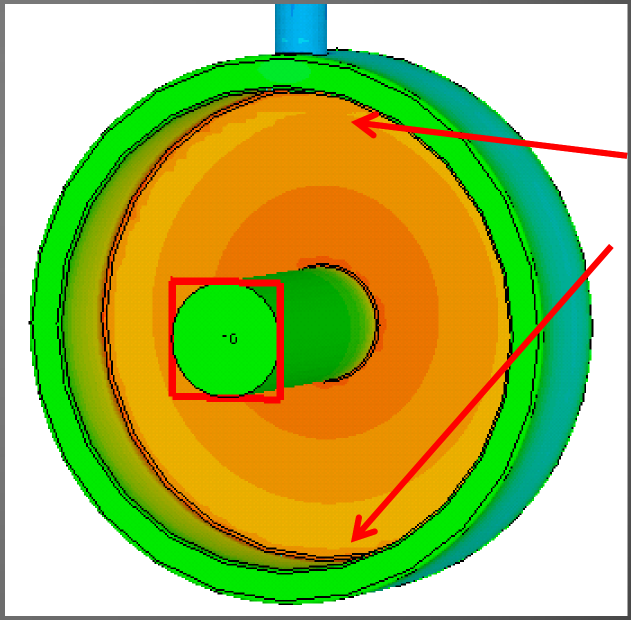
Prototyping and Measurements: Body

Perform measurements and compare with expectation

- The prototypes could differ from the expectation, reasons has to be found out: material roughness, geometrical error, brazing/welding influence, feedthrough







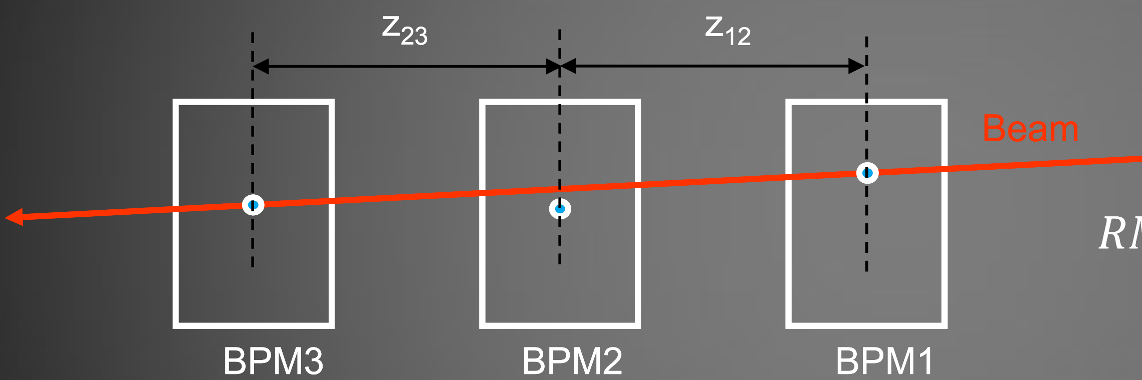
Field distribution due to one antenna distorted, symmetry broken

Difference of resonance frequency between expectation (simulation) and measurement of reference resonator by 6 MHz; systematic shift due to non-perfect simulation

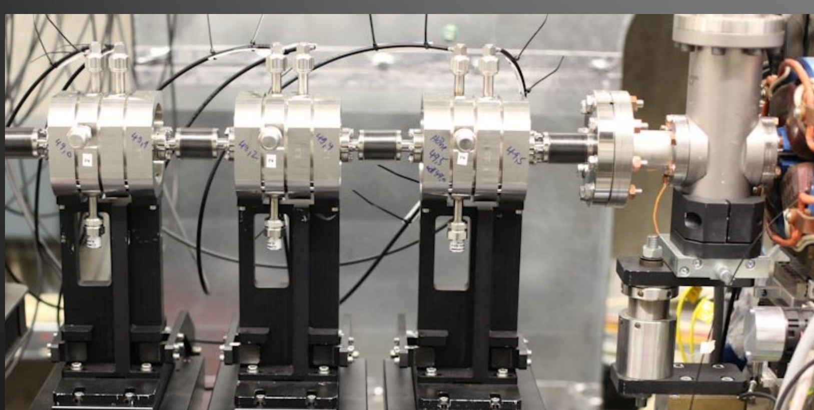
Prototyping and Measurements: Body

Install 3 BPMs to measure and verify resolution

- Both outer BPMs predict beam position at BPM2, difference result in residual
- RMS value corrected by geometric factor results in resolution *R*



$$RMS^2 = R_2^2 + \left(\frac{z_{12}}{z_{13}} R_1\right)^2 + \left(\frac{z_{23}}{z_{13}} R_3\right)^2$$



When all three BPM systems are similar the resolution $R=R_1=R_2=R_3$

Photo of a cavity BPM triplet test facility at FLASH

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Selection of Companies

For a large number of BPMs one has to outsource the production

- Not all companies are able to produce feedthroughs and BPM mechanics with the required precision
- Procurements rules: call for tender could results in not qualified company
- Following procedure for feedthrough and BPM mechanics has been applied to qualify the company:

Qualification: call for tender of a small number of items (pre-series)

↓

Test production: identify companies which produce with required quality

↓

Call for tender for the complete series for the qualified companies

↓

Quality controls during all production processes

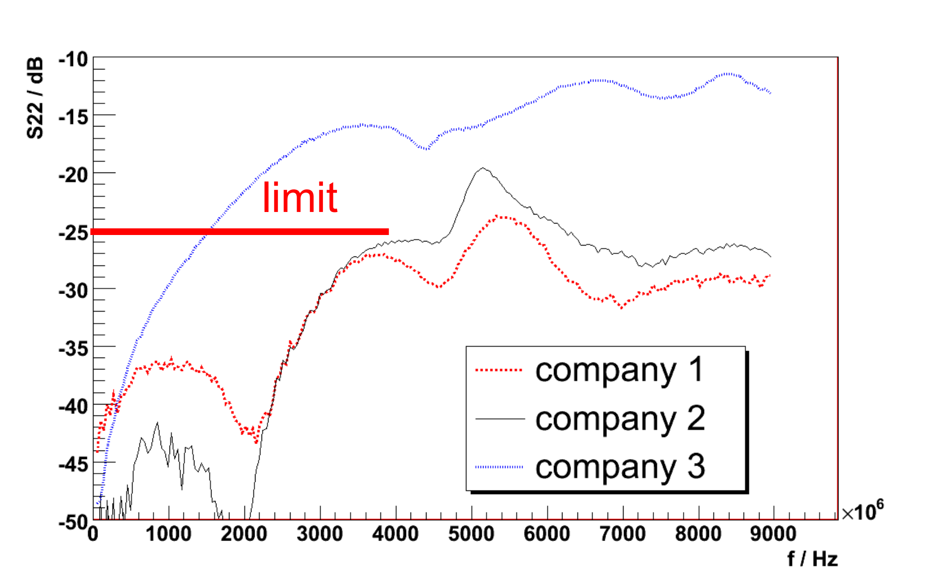
↓

Final check of items including documentations

Selection of Companies

Example: pre-series production results of feedthroughs

- Open international Tender for 180 items: Choose 3 companies
- Company 1: 90 items; company 2: 45 items; company 3: 45 items
- Two companies delivered within specifications: below -25 dB up to 4 GHz



1 feedthrough lost inner pin (company 3)

Photo: D. Nölle

Decision for the series production of 700 items based on price of company 2

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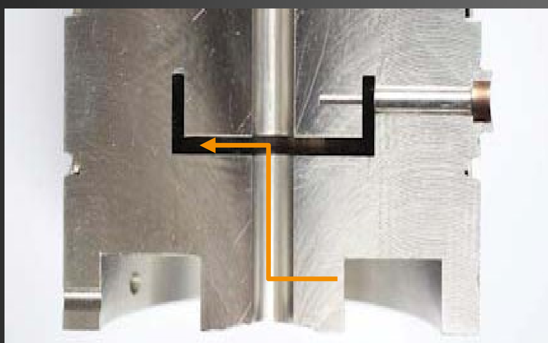
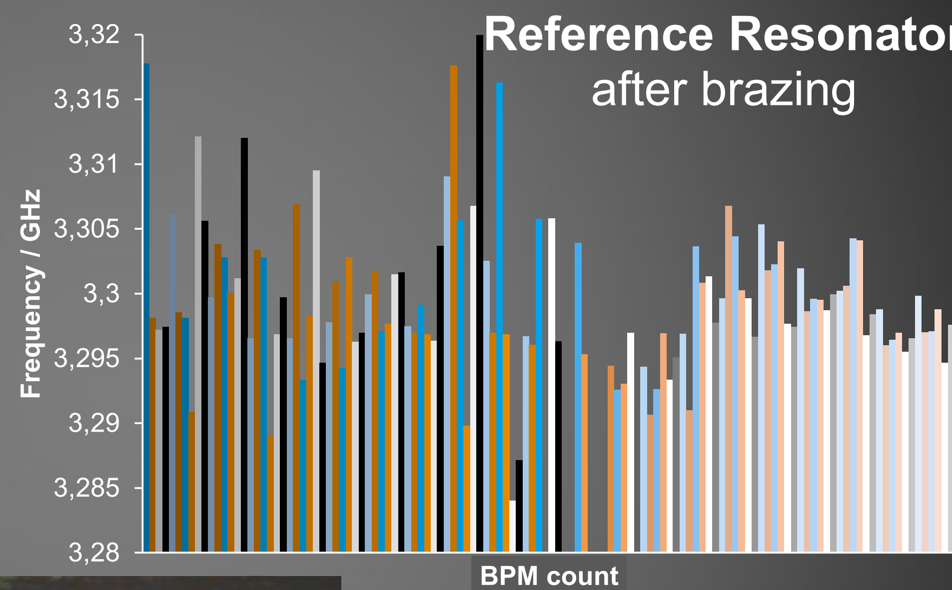
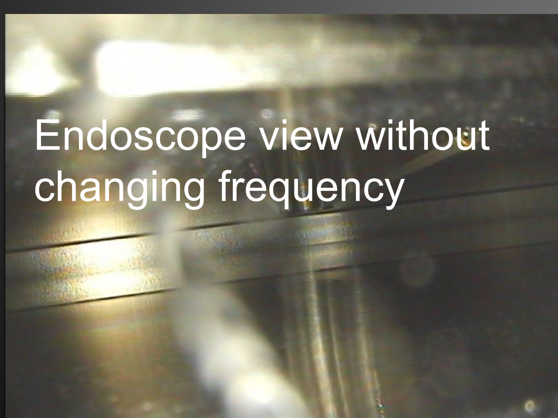
Series Production and Quality Tests

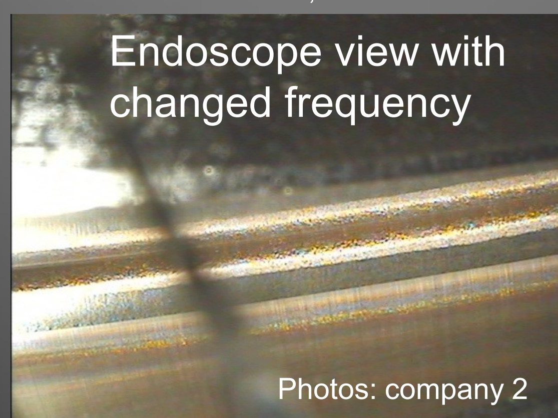
During main production the BPMs always check quality (closely contact to company)

Use commissioned test setup at company









Large resonance frequency change after brazing correlated with brazing material in the resonator

Increased brazing foil inner diameter helped

Series Production and Quality Tests

Accuracy (absolute position) for

Button BPM

- measurement TDR or network analyzer to obtain broken feedthrough and find similar transmission buttons to pair them
- Precision of mounting of button defines deepness of button: 1:1 of signal precision
- In addition cable properties influence accuracy when difference method is applied: cable have to be tuned

Button BPM feedthrough transmission measurement with reference

Precise mounting of feedthrough on body in clean room

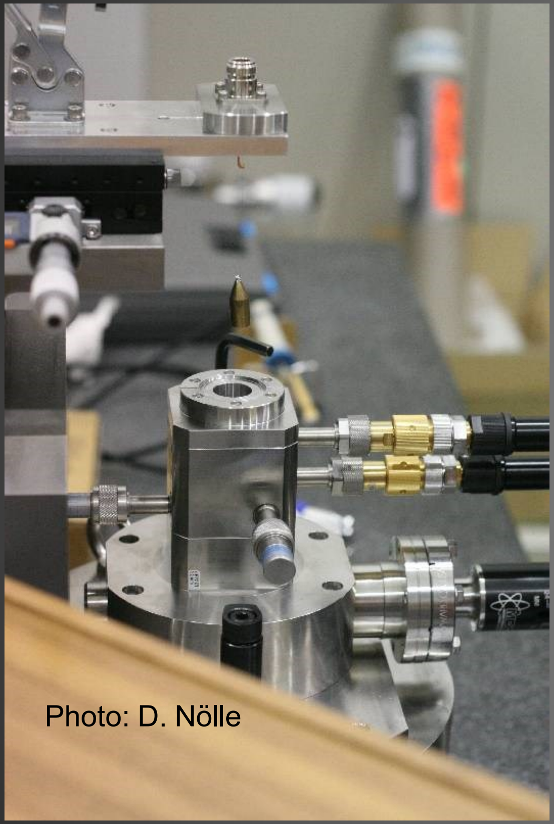
Photo: D. Nölle

Cable measurement in accelerator room

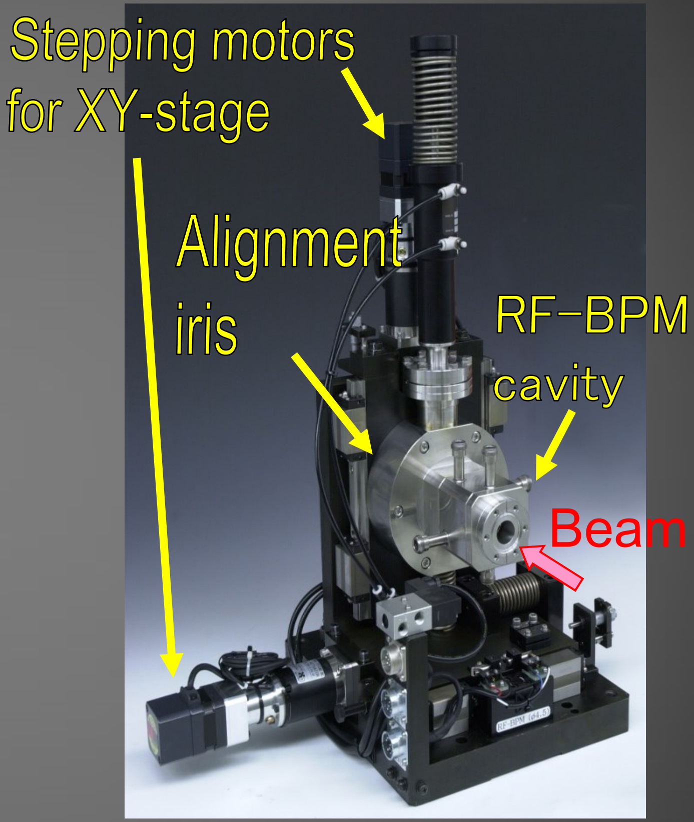
Photo: D. Treyer

Series Production and Quality Tests

Accuracy (absolute position), example here cavity BPM for SACLA



Setup of BPM with wire and network analyzer to measure electric center compared to mechanical center in laboratory



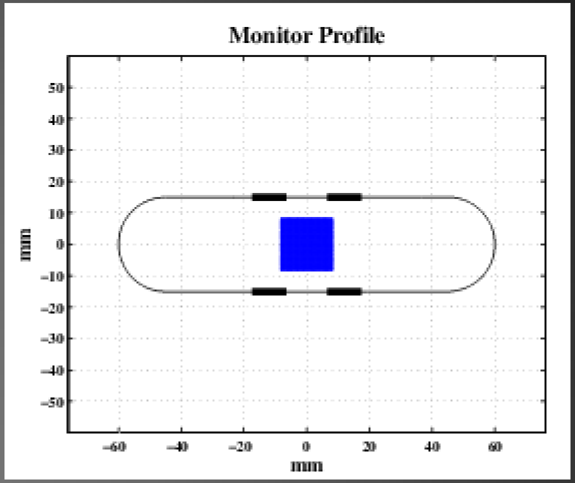
Setup of BPM with alignment iris for laser adjustment installed at the beamline: position accuracy 4 µm
Thanks to H. Maesaka et al.

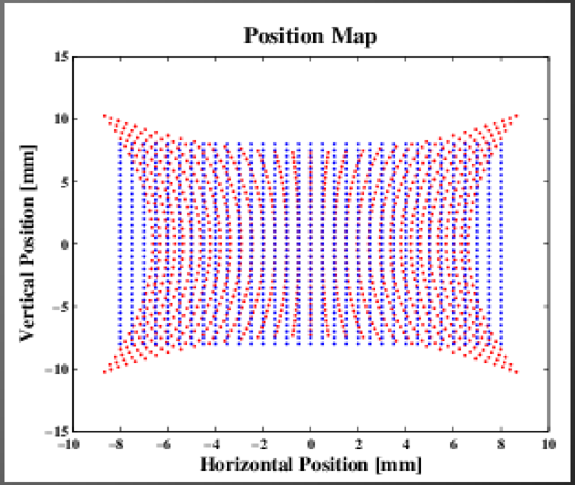
Content

Operation at the Accelerator

Commissioning with beam

- In parallel design, production, tests, (maybe improvements) commissioning of front-end electronics
- ADC and if necessary FPGA
- Cabling (radiation hard: connectors and cables)
- Trigger, synchronization
- Map correction, see example of a flat beam-pipe
- Prepare calibration: with remote mover (expensive and bellows are necessary) and/or steerer (larger uncertainty)





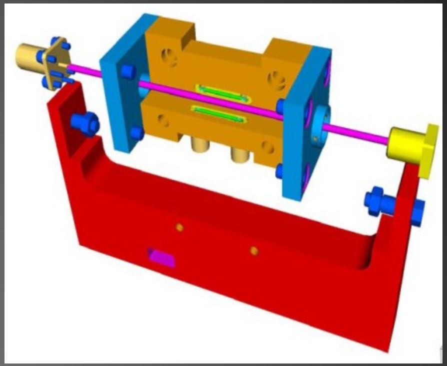
Thanks to G. Kube

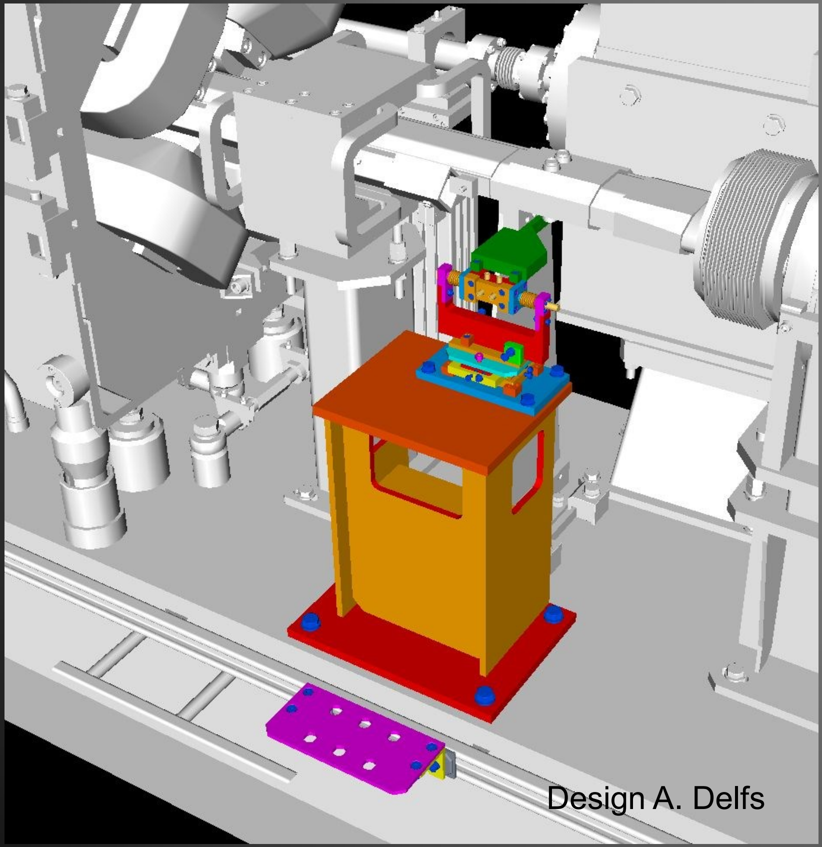
DESY

Operation at the Accelerator

At PETRA III: monitoring of the BPM movement due to beamline heating with respect to the ground

- Using wire connected with ground floor and with 4 striplines connected to beamline



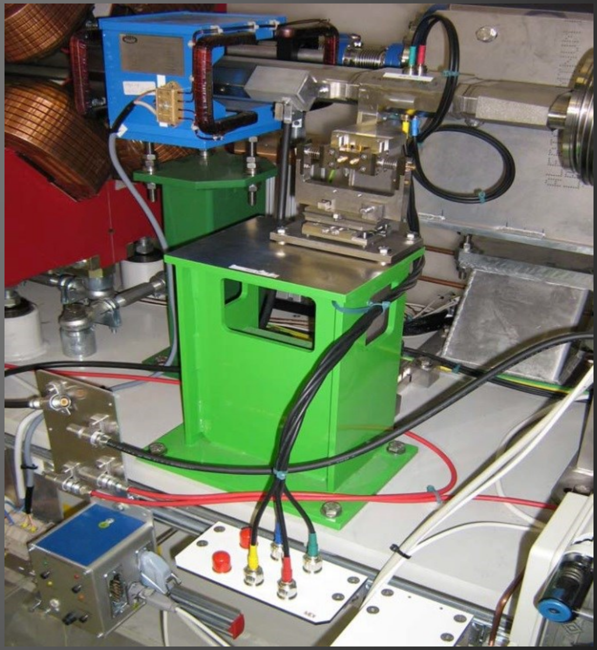


145 MHz signal with λ/4-wire antenna and BW 1 Hz

Linear dynamic range: 2x2mm^2

Position resolution < 1 µm

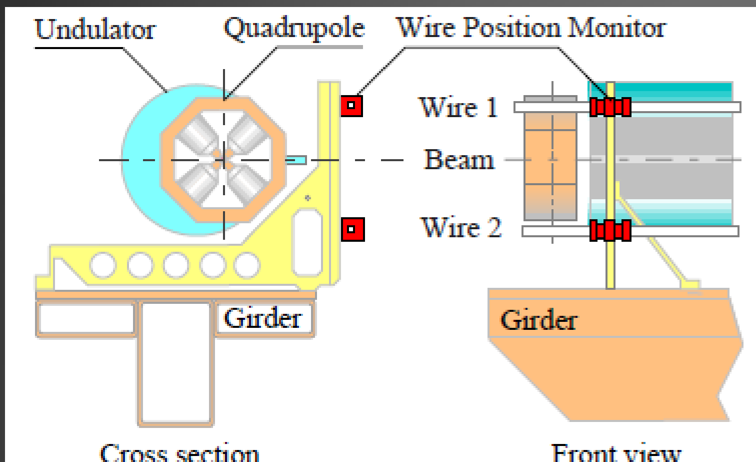
Observed 4.5 µm movement

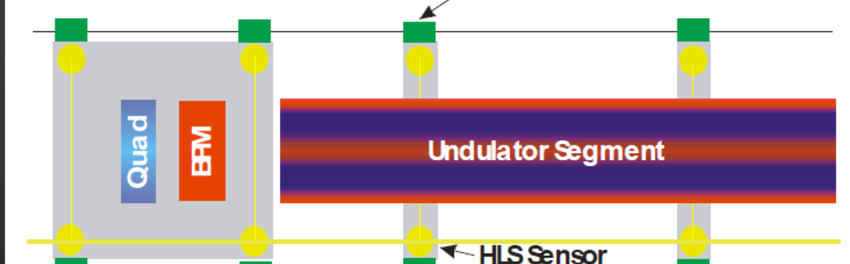


provided by A. Delfs

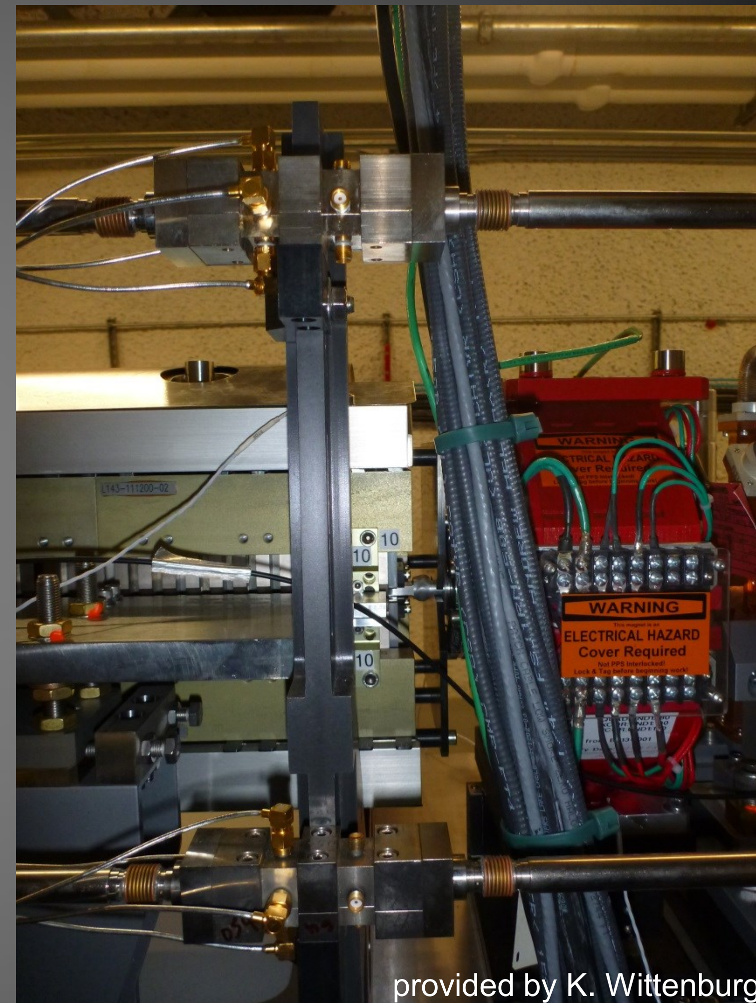
Operation at the Accelerator

- LCLS monitoring of beam pipe





Monitoring System Layout, HLS (yellow), Wire System (green)

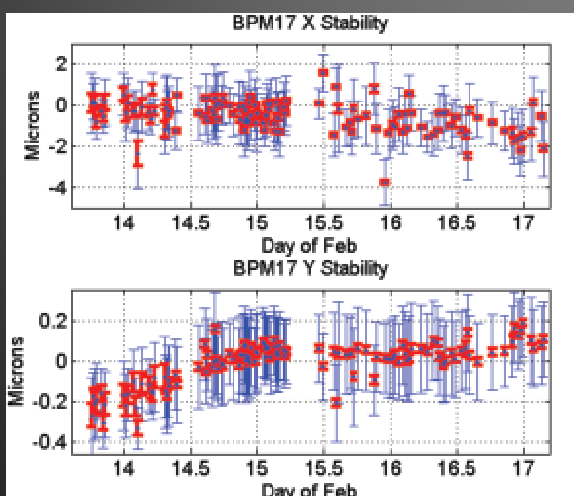


provided by K. Wittenburg

Two (140 m) long wire, 4 sensors/undulator; more than 1 µm movement observed

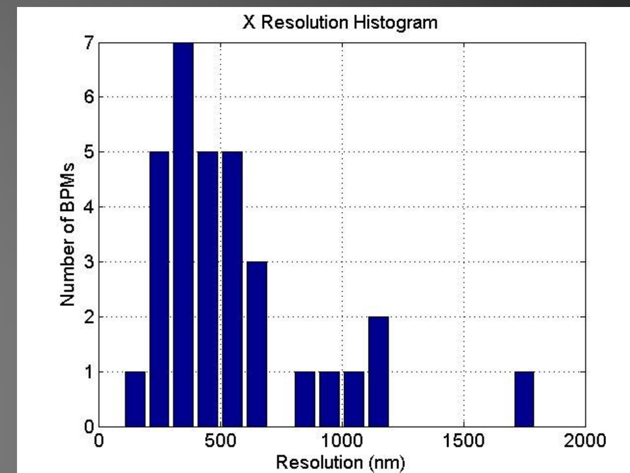
Operation at the Accelerator

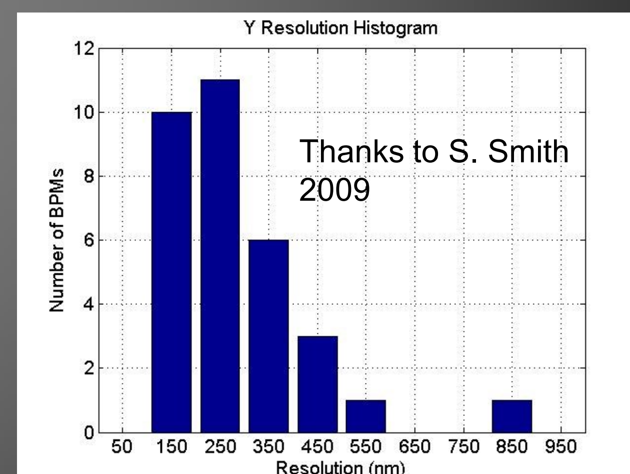
Operation of LCLS cavity BPMs



Stability measurements

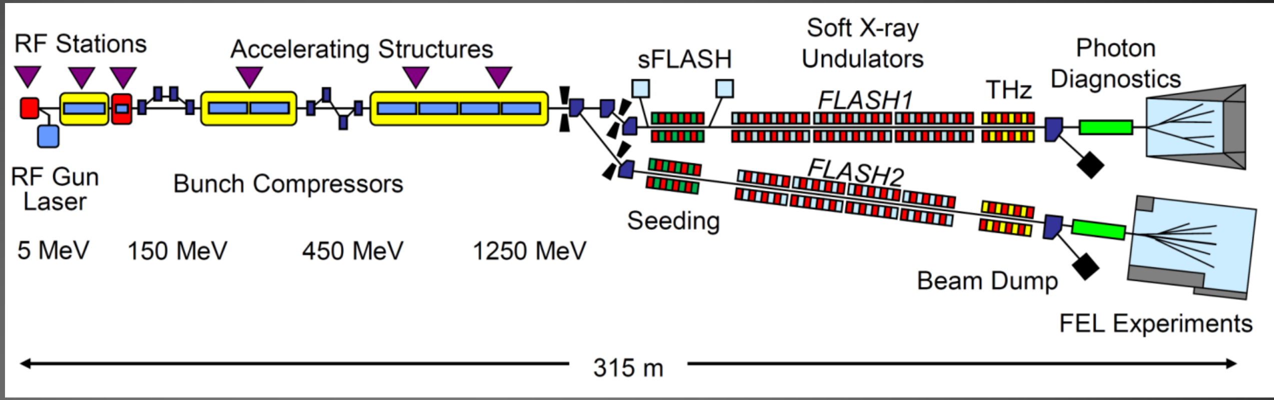
Distribution of measured resolution:





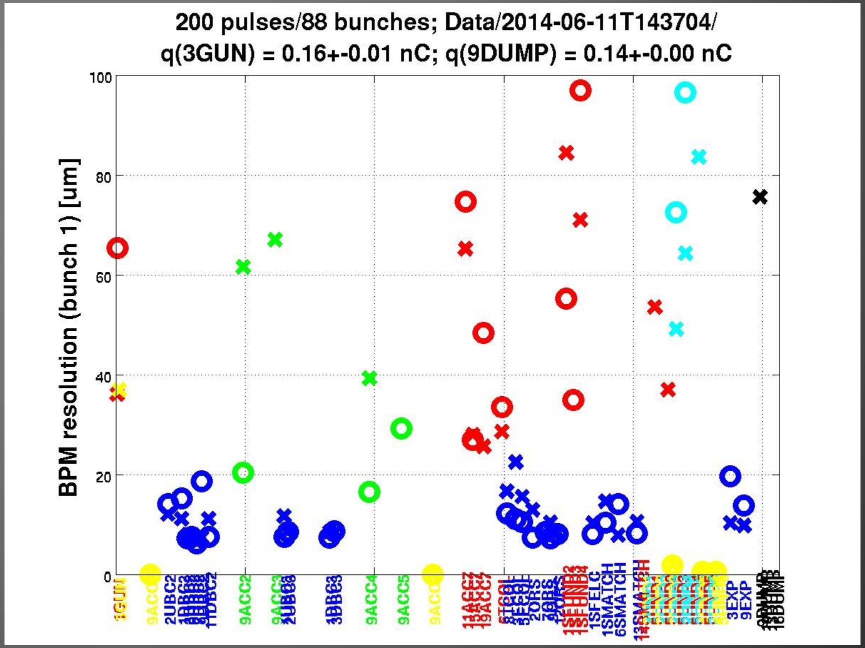
Operation at the Accelerator

Sketch of FLASH beamline



Resolution of each BPM along FLASH beamline

- Blue: stripline
- Red: button
- Green: old cavity without slot
- and others



Thanks to N. Baboi

Summary

Development of BPM system:

> Collect all requirements and boundary conditions
> Simulate design: optimize and tolerance study; mechanical tolerances are not the only sources of BPM performance deviations (brazing, feedthrough, …)
> Attention to dissipated power (not only to BPMs)
> Attention to performance and delivery of feedthrough: check design before BPM production
> Produce prototypes; extensive test to check performance, optimize design for series production; compare with requirements
> For a large number of items: initiate pre-series to find and train companies for the final production
> Control each production process steps
> Additional actions to match accuracy (RF properties, cable, mechanical alignment, support …)
> Commission the system with electronics (calibration principle established, correction of map), check performance

Summary

Do not forget:

- Spare items with respect to MTBF
- Availability of components (electronics, feedthroughs, …)
- Documentation of each item project phase for reordering

Thank you for your attention!