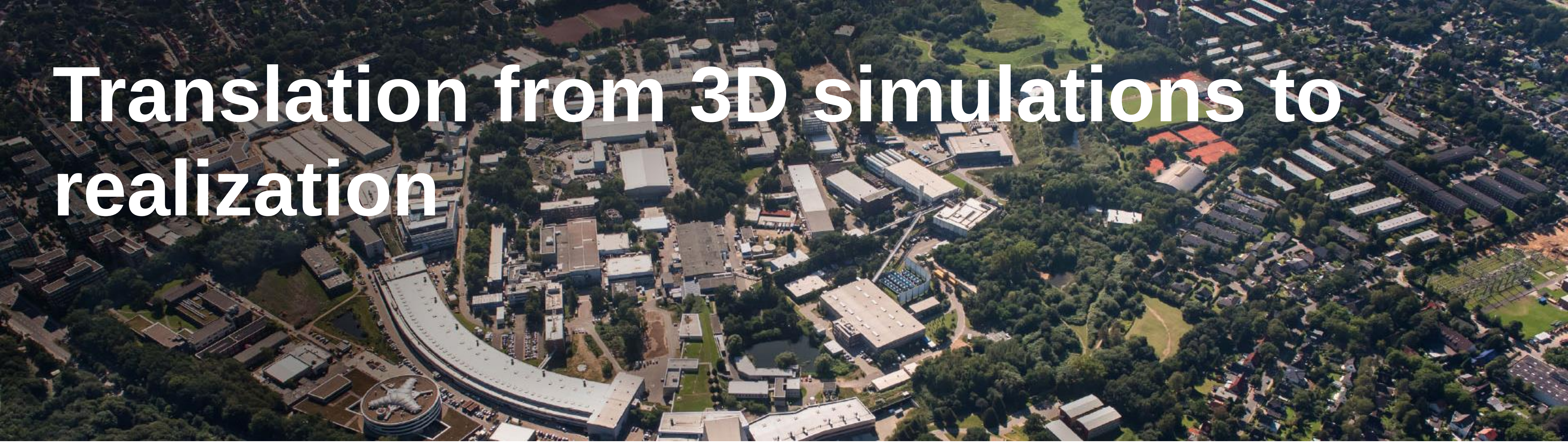
Translation from 3D simulations to realization



Dirk Lipka and Silke Vilcins, MDI, DESY Hamburg, Germany
Online, June 2021

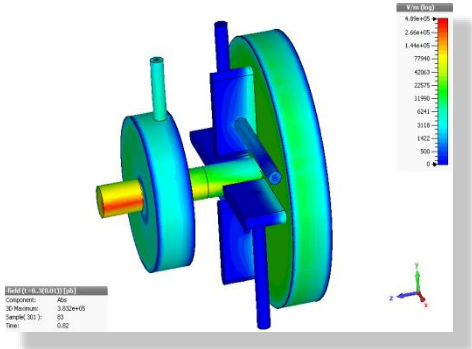
Materials and Engineering Technologies for Particle Accelerator Beam Diagnostic Instruments

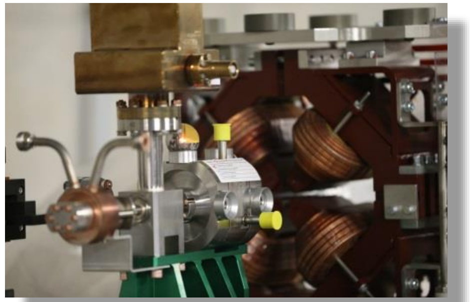
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

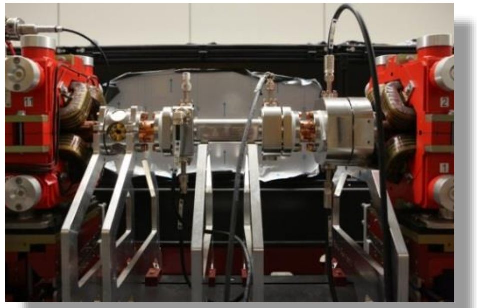
Outline

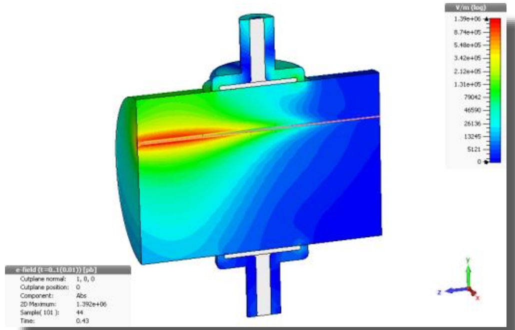
- Requirements
- Design with Simulations
- Prototyping and Measurements
- Selection of Companies
- Series Production and Quality Tests
- Summary

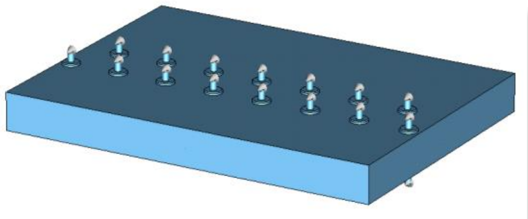
Example with Beam Positions Monitors (BPMs) focused on mechanical aspects

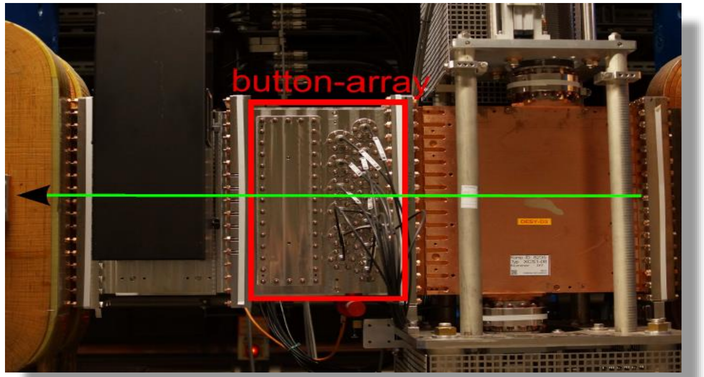


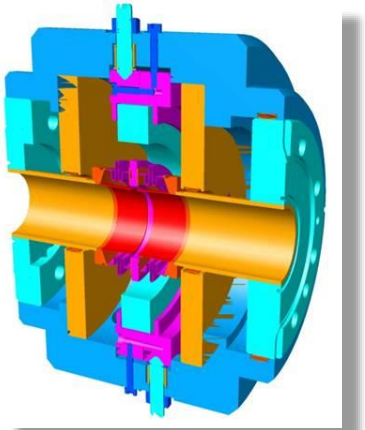


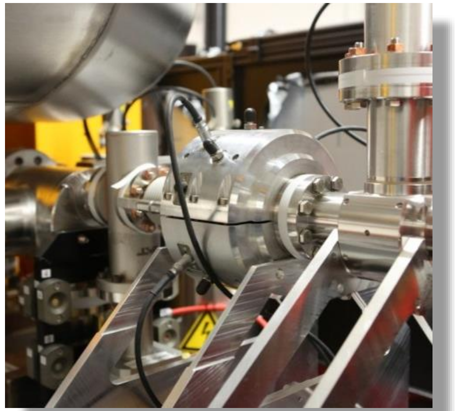












Requirements

Need to be fixed before development starts (but in reality they change sometimes)

Top Level Requirements

- **Resolution** (relative noise): influenced by type of device, electronics, ADC granularity …
- **Accuracy** (absolute value): influenced by mechanical tolerances, alignment accuracy, cable, support vibration, thermal effects …; need test system and alignment tools
- **Dynamic range:** in which range the physical values need to be shown;
- **Detection threshold:** e.g. 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

Additional conditions need to be defined (hopefully they do not change when development is finished)

- Shape and sizes of beam tube (round, elliptical, rectangular …)
- Number of items
- Item space of the device
- Environment temperature: device at cryogenic temperatures?
- Area for support, vibrations
- Vacuum aspects like pressure and particle reduced area
- Distance between device 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, firmware, server, …
- Low maintenance effort

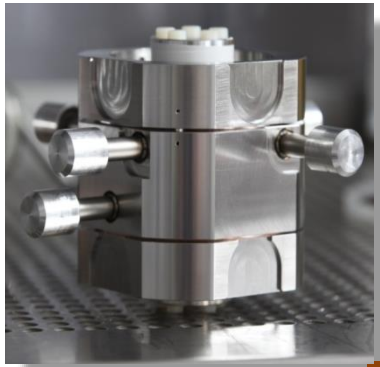
Requirements

Divide system in mechanics and electronics subsystems

- Here only mechanical aspects will be discussed
- But the system consists of
  - Mechanics
  - Electronics
- To fulfill top level requirements the separate mechanics and electronics behavior have to be taken into account
- Define necessary parameters of the mechanics as inputs of the electronics and check the system performance
- → for more efficiency: development of mechanics and electronics in parallel

Example for development of BPMs:

- **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



European XFEL cavity BPM, photo D. Nölle

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

Design with Simulations

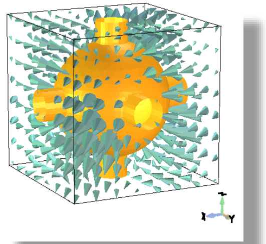
Define path of development

- Analytic expressions define design (assumptions are necessary) and prototyping with intense tests, followed by redesign; time consuming
- Predict properties of design starting with analytic results and followed by simulations; time saving (simulation tools are very powerful, user-friendly, help service, examples and precise in combinations with fast computers)
- Use existing design (colleagues or company) and adapt it to new requirement and conditions with simulation

Examples of simulations tools: CST now part of Dassault Systemes, HFSS, GdfidL, COMSOL, ACE3P from SLAC, etc.

CST → DASSAULT SYSTEMES

The GdfidL Electromagnetic Field simulator



COMSOL

ACE3P (Advanced Computational Electromagnetics 3D Parallel) Code Suite

SLAC

…

	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

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

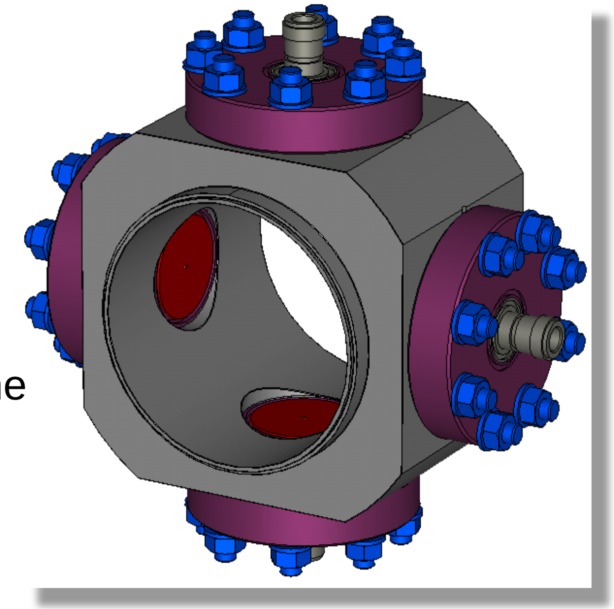
Total time shorter than sum because of parallel work

Design with Simulations

Import and Export of 3D Model

- Nowadays simulation tools are capable to import existing 3D models for design adaption and optimization
- But the complete model includes much more details than necessary (e.g. screw thread …) which would increase number of mesh cells and therefore increase simulation time
- → reduce model to necessary parts: this is the work of a simulator (like me) to judge which part can be simplified to simulate effective

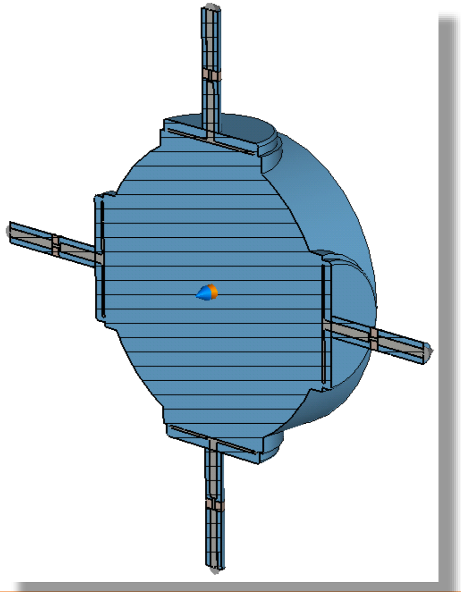
Button BPM design for the European Spallation Source (ESS)



Reduction of design to the vacuum part with button and feedthrough

Finished RF design conversion to mechanical design

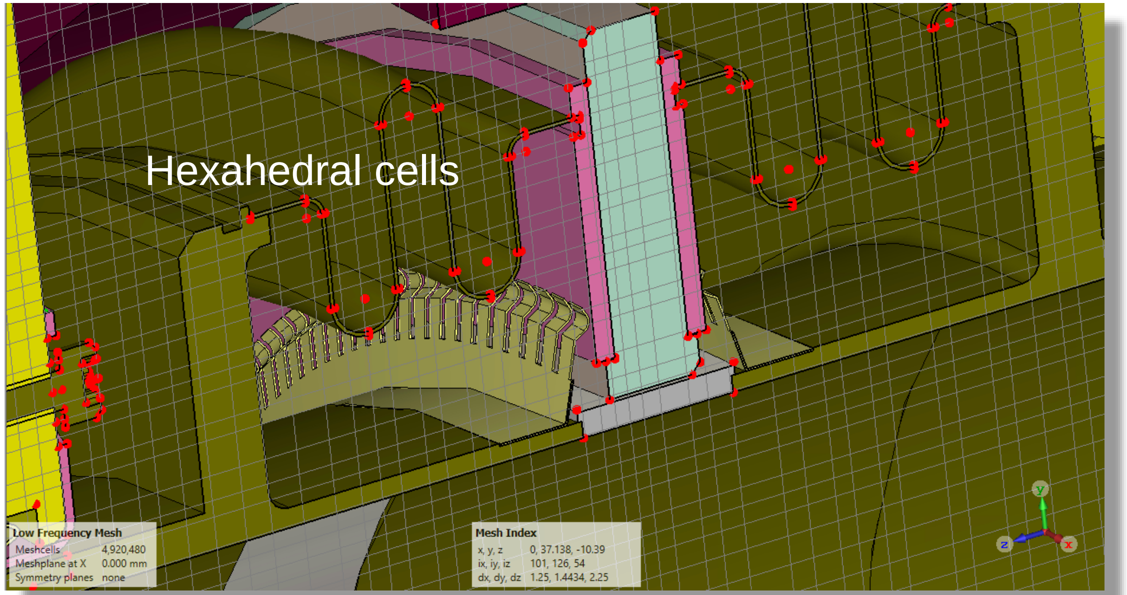
RF equivalent geometrical simulation model (cut view)

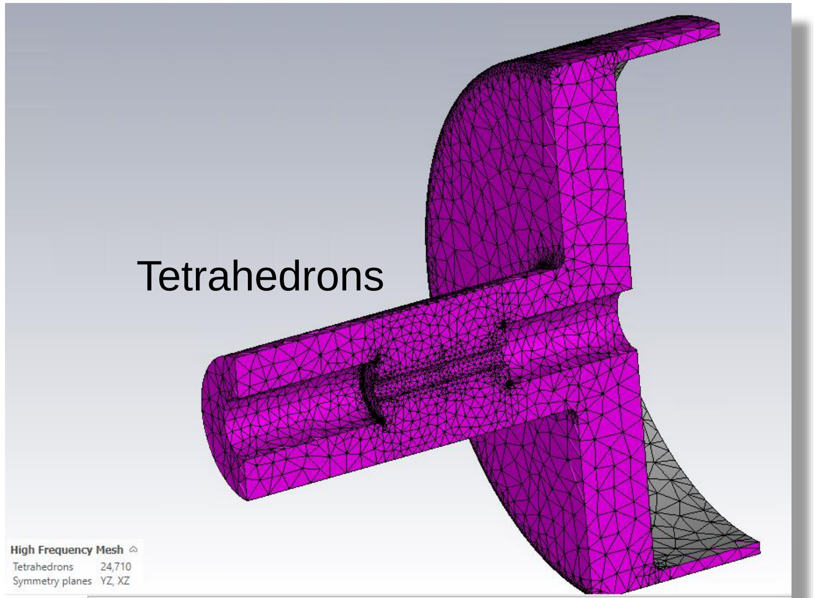


Design with Simulations

Check simulation Model

- 3D simulation tools are working with subdivision of a continuous geometric space into discrete geometric and topological cells
- Each mesh cell in an ideal case should be homogenously filled and at maximum only contains 2 different materials per mesh
- Different mesh cell geometries available for different simulation tools; find the suitable mesh cell (e.g. Hexahedra [topological cubes] or Tetrahedra)

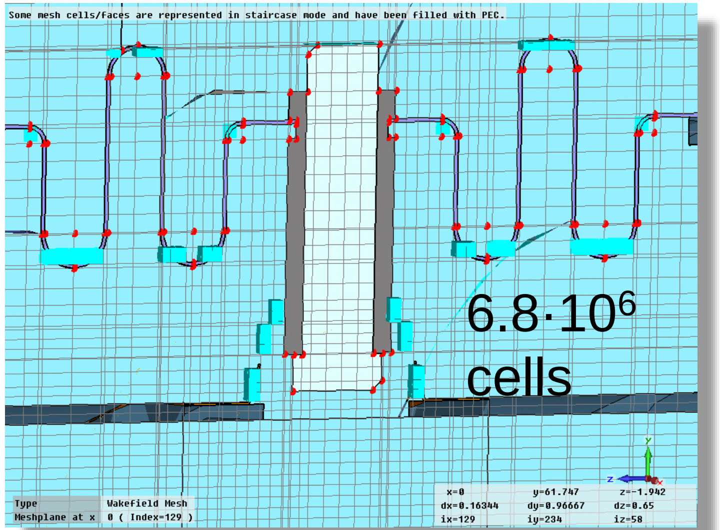


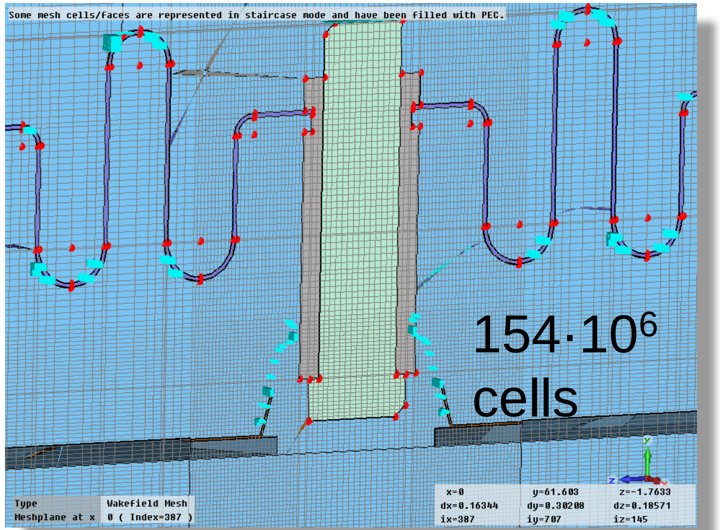


Design with Simulations

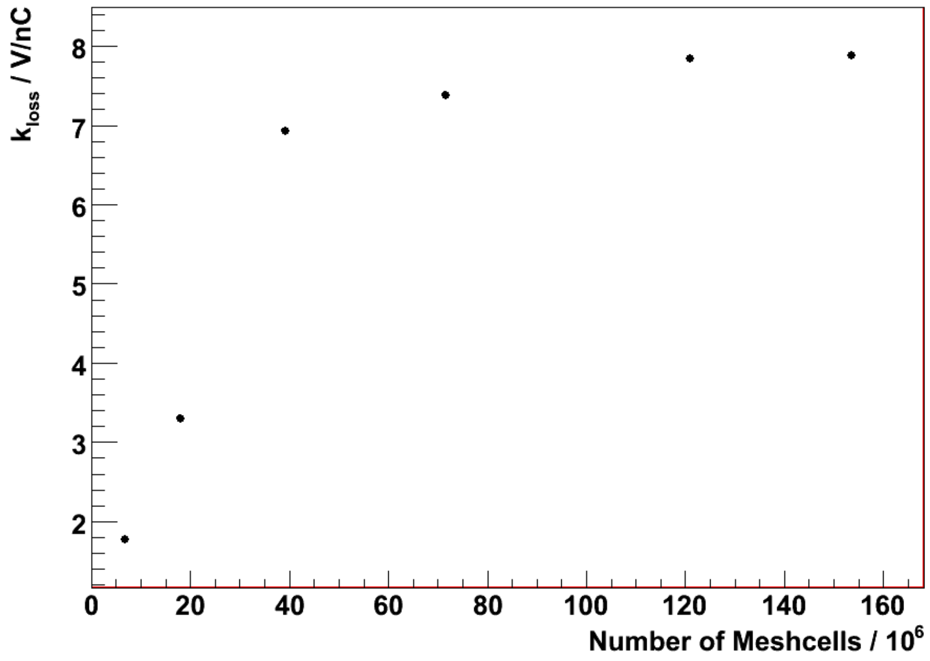
Check simulation Model

- Sometimes mesh cells are not able to smoothly follow the design
- Reduce mesh size until a convergence is observed





Hexahedral mesh does not follow the bellows and spring, need smaller mesh size



- Here simulation of loss factor as a function of number of mesh cells

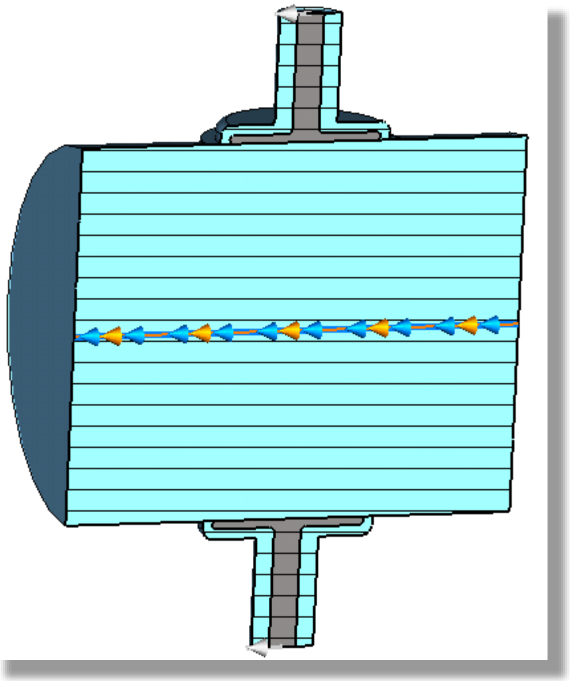
- In general: check the model mesh cells (no short-circuits), compare with **analytical expression**, compare results with **different solvers** (**time** and **frequency domain**), check **convergence**

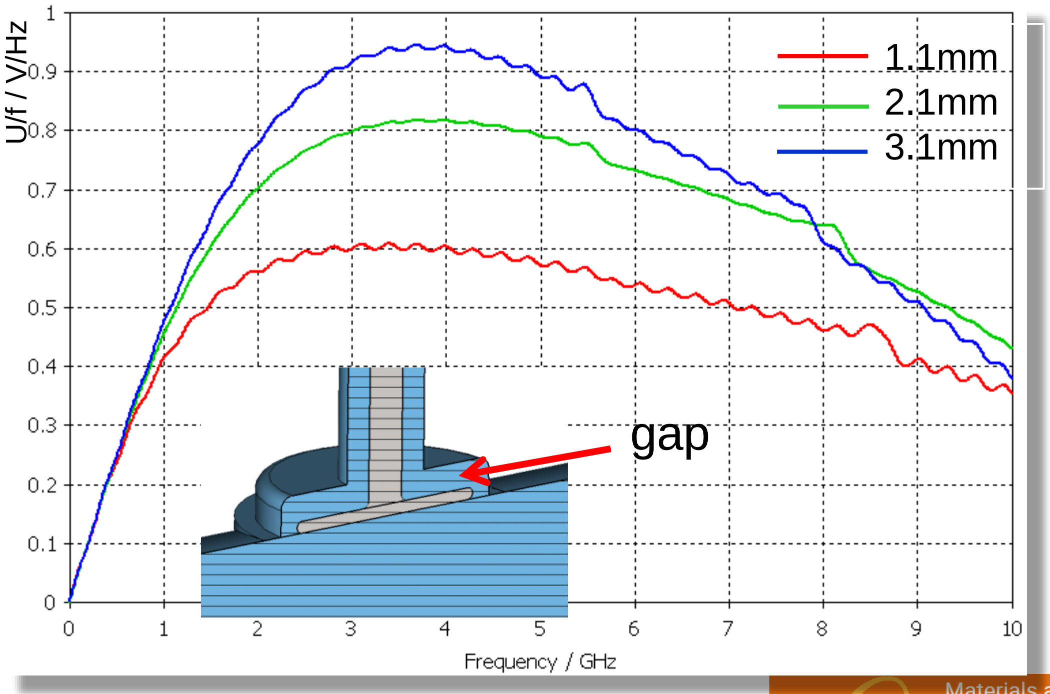
Design with Simulations

Optimize Design

- To improve signal/noise ratio increasing sensitivity
- But be attention to all other parameters too: resonances, producibility, components nearby, avoid virtual leaks , …

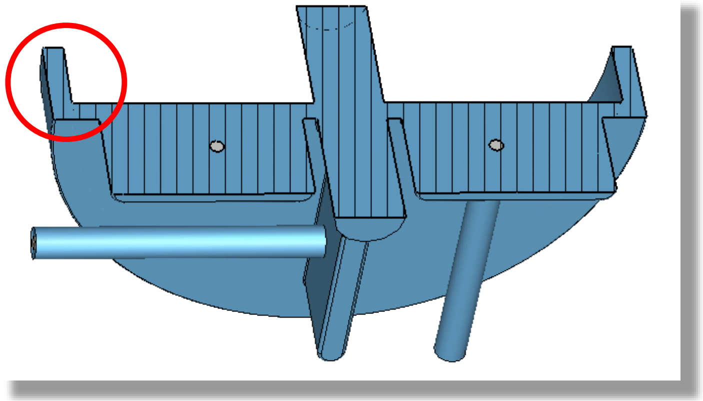
- Example XFEL button BPM design with different gap distance
- Increased amplitude up to 10 GHz without resonances

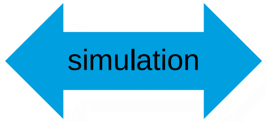




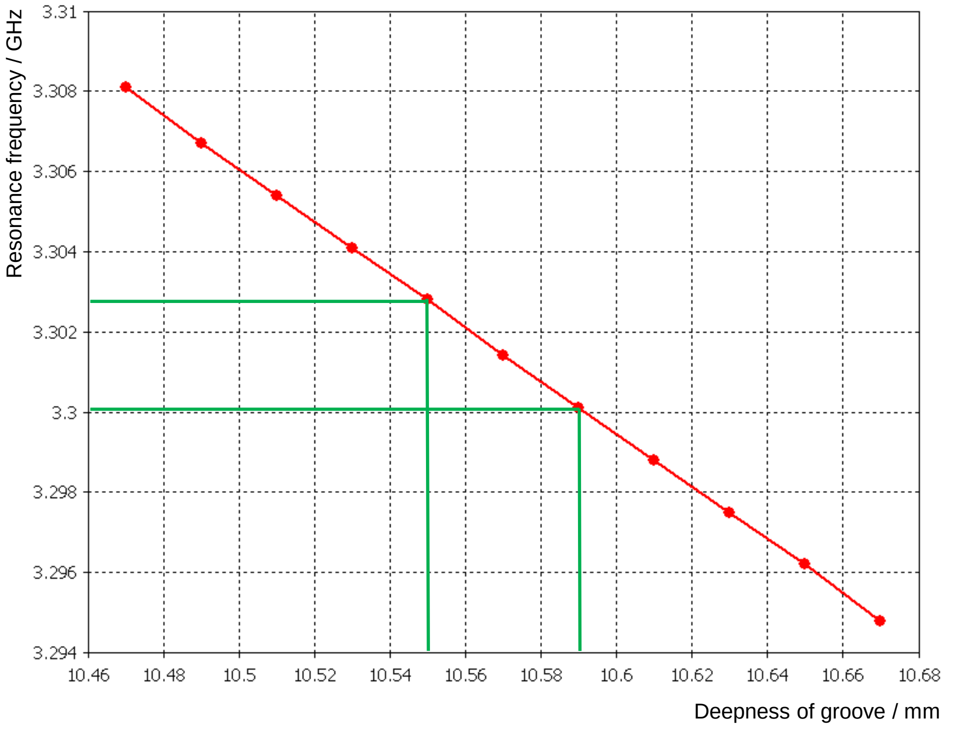
Design with Simulations

Tolerance Studies for Construction



- Investigation of signal influence due to tolerance: discussion between designer (dreamer) and constructor (realist)
- Shown example: bandwidth of the electronics defines the mechanical tolerance
- Interplay: electronics capability  mechanical feasibility

- Reduction of system price with looser tolerance due to electronics capability



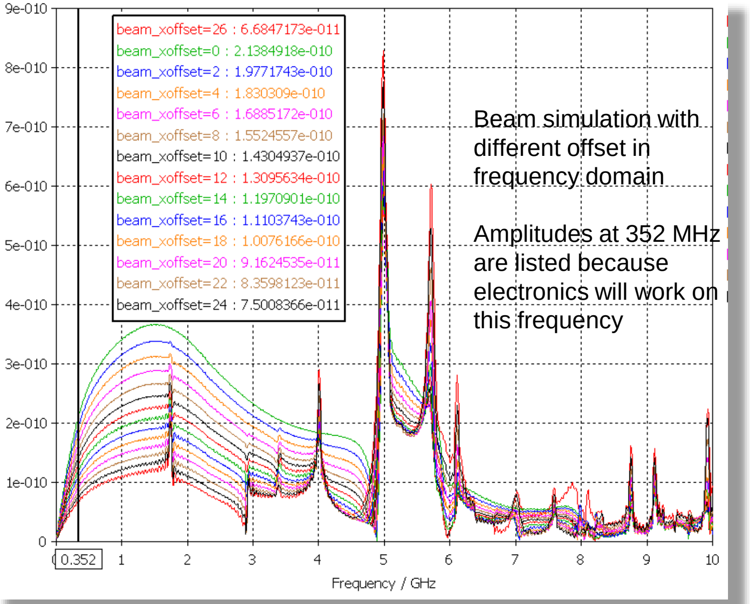
- Real blend radius on edges need to take into account (from a physicist point of view edges could be sharp but not in reality)
- All separate mechanical tolerances necessary for production
- Sum of all tolerances defines worst case, correlations of each tolerance results in smaller reaction, need to be checked but time consuming due to a large number of parameters

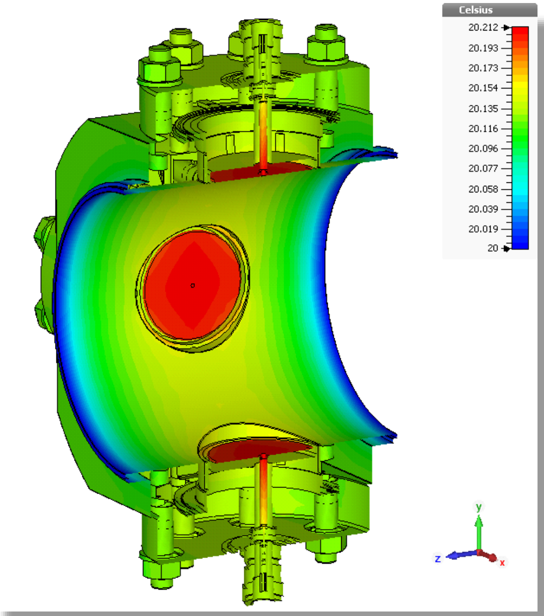
Design with Simulations

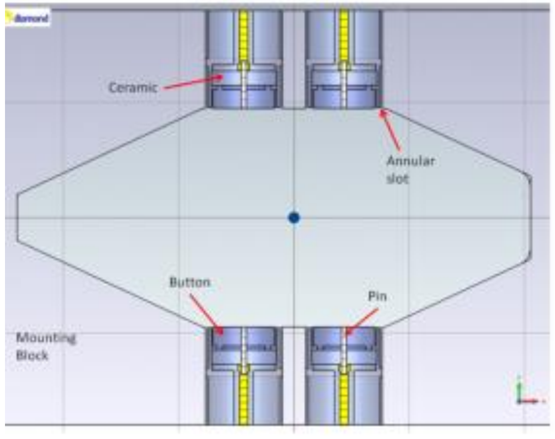
Dissipated Power

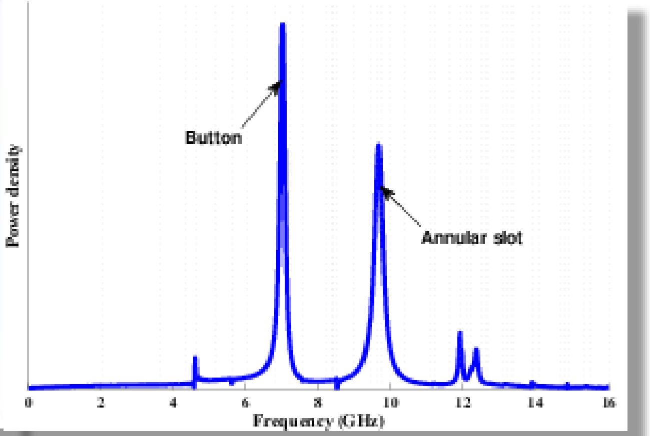
Example: button BPM for ESS

- Observed strong resonance above 5 GHz
- Simulation of wake loss and Eigenmode as input thermal (attention to thermal boundary conditions, conductivity, convection and radiation)
- Result: only negligible temperature rise









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

- Example of DLS button where the annular slot contributes to the power loss

Do not observe this in your machine

Photos taken from A. Novokhatski

Design with Simulations

Dissipated Power important for high duty cycle accelerators with high beam current

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

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

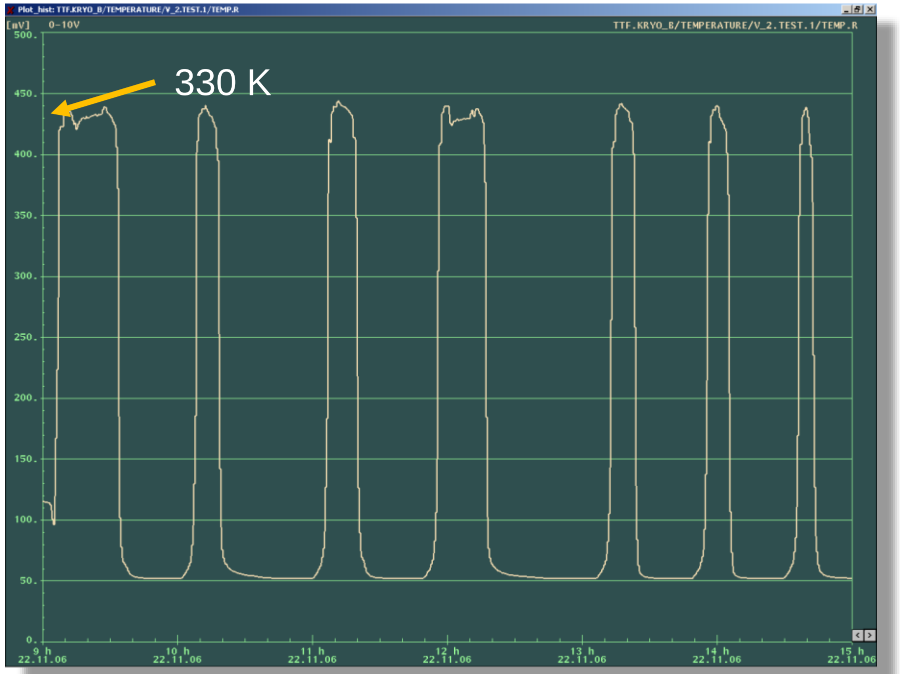
This affects the design!

Prototyping and Measurements

Vacuum Design

- Already at the design stage **contact companies** to discuss the feasibility (like this workshop)
- This gives us the possibility to increase the possibilities for fabrication and distribute ideas
- Could include **special company solutions** into the design to improve it, but then we are dealing with secrets which could be a problem with open scientific work, need a non-disclosure agreement ☹
- Better global solutions but maybe not possible
- For open scientific presentations with NDA reduce details ☺

- **Vacuum feedthrough** are one critical important sub-component of vacuum devices
- Example feedthroughs for cryogenic chamber in a test bench

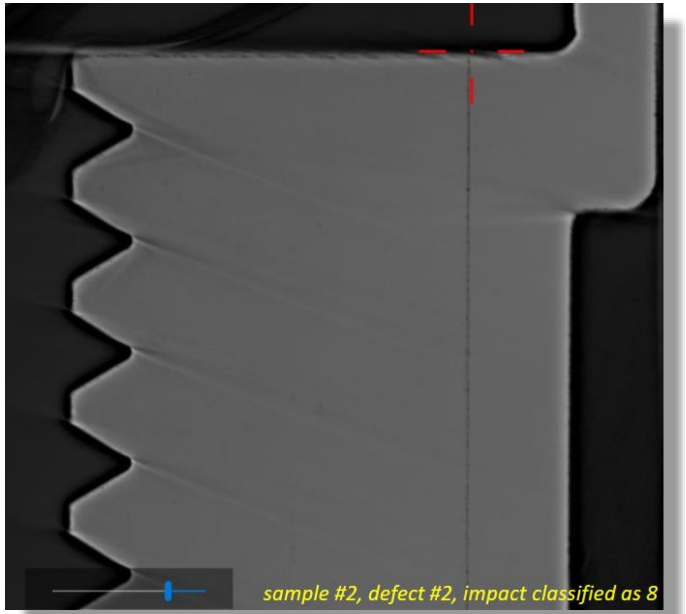


Prototyping and Measurements

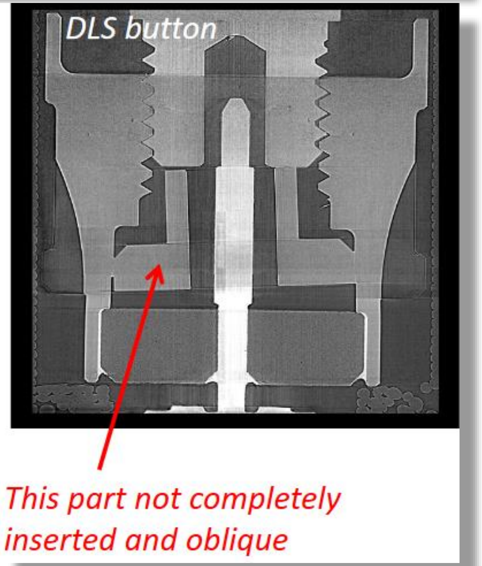
Vacuum design Test Check List

Courtesy Friederike Ewald, ESRF at DEELS Workshop 2018

- **Visual check:** flange geometry, gasket, surface (no scratches)
- **Check Material:** should be vacuum tight (ESRF observation of channels), hardness: flange geometry should not change after use
- **Check performance:** measurement of transmission and reflection, maybe need adapters for sub-systems



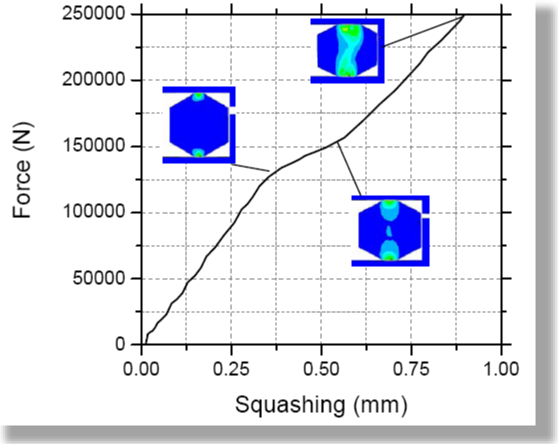
Computer Tomography measurement show: Channel in feedthrough



Misalignment in feedthrough

Feedthrough with adapter

Force vs. deformation of Aluminum gasket



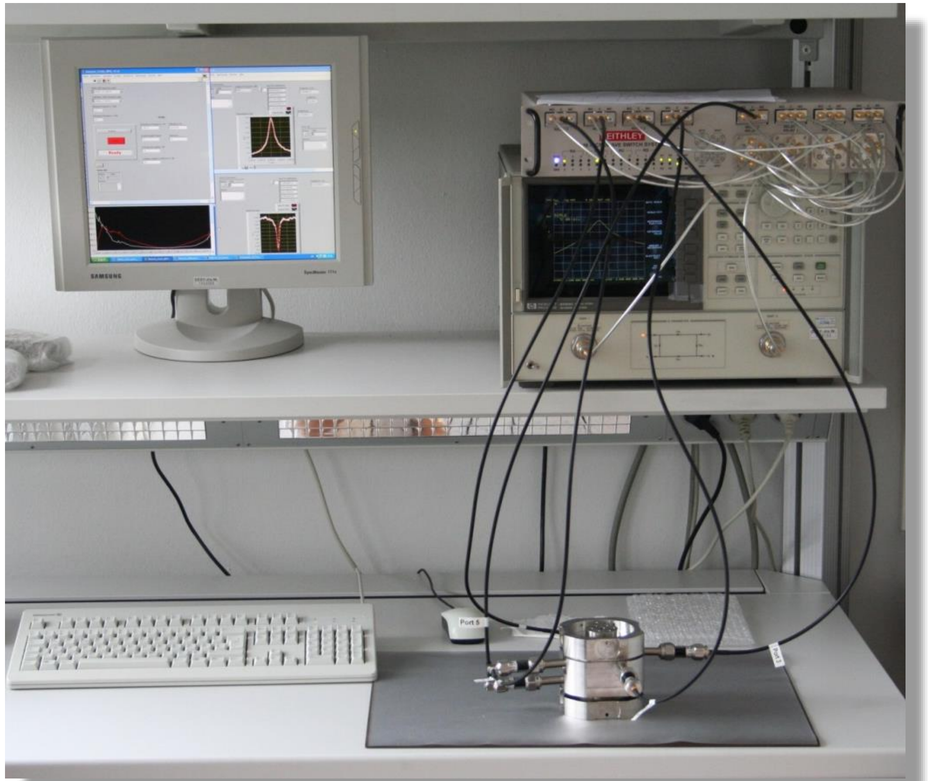
Materials and Engineering Technologies for Particle Accelerator Beam Diagnostic Instruments

ARIES

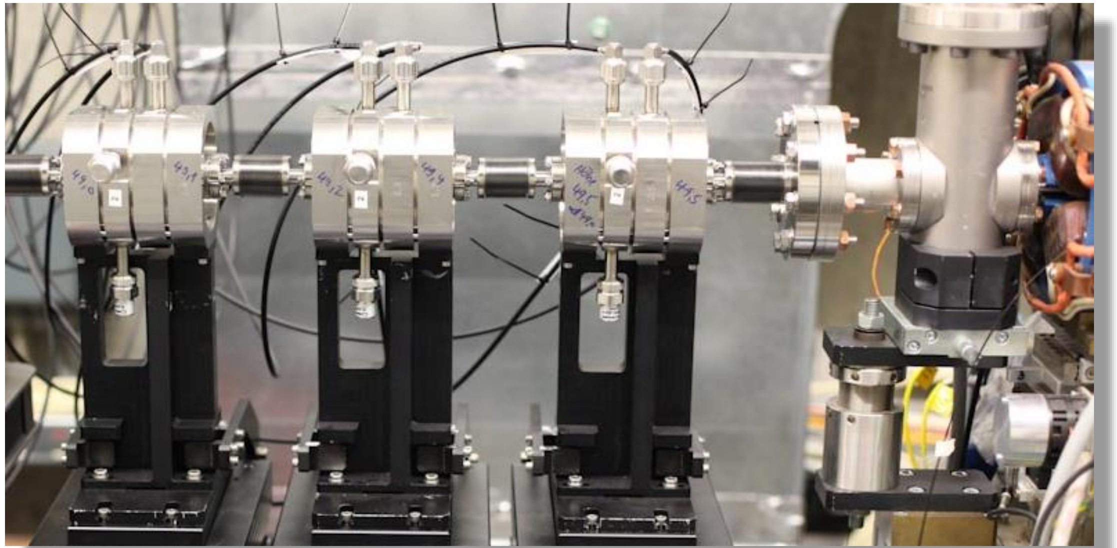
Prototyping and Measurements

Test the complete system, when possible with beam

- Laboratory test:



- Test in accelerator



→ Selection of companies for series production

Selection of Companies

Prototyping and Measurements used to test quality of companies

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

- Not all companies are able to produce mechanics with the required precision
- Procurements rules: call for tender could results in not qualified company
- Following procedure for mechanic devices 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

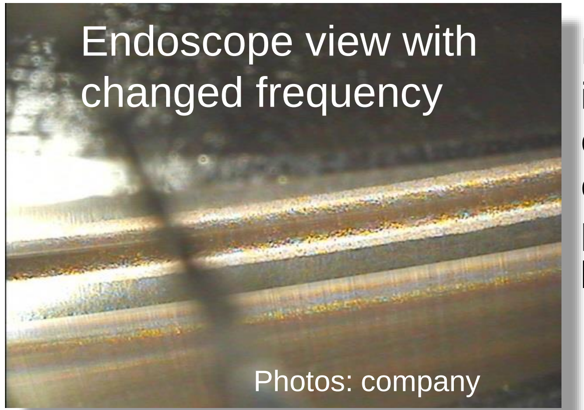
↓

Final check of items including documentations

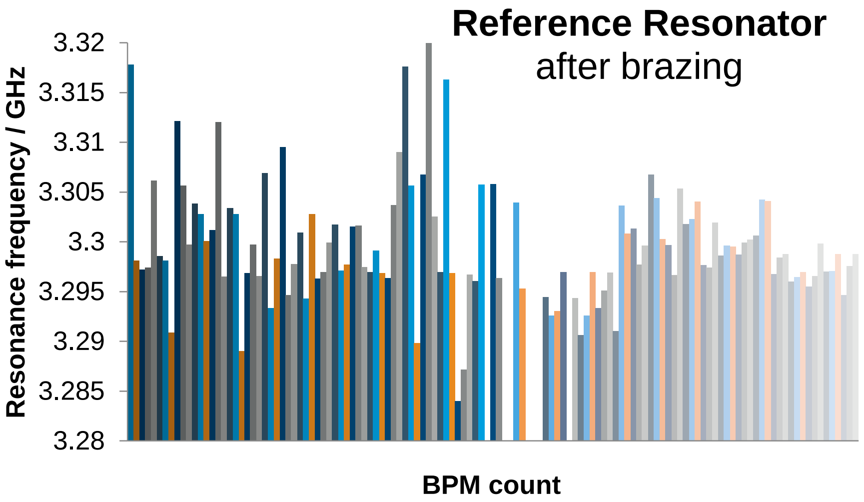
Series Production and Quality Tests

Check each step of production

- When possible check quality of pieces during sub-production steps to react on pieces with outer limits
- Produce pieces in batches and check them, give feedback to company for improvements
- Finally again check visual, material and performance



Brazing material flow into resonator changed frequency, change of brazing procedure avoided larger frequency



Precise mounting of feedthrough on body in clean room
Photo: D. Nölle

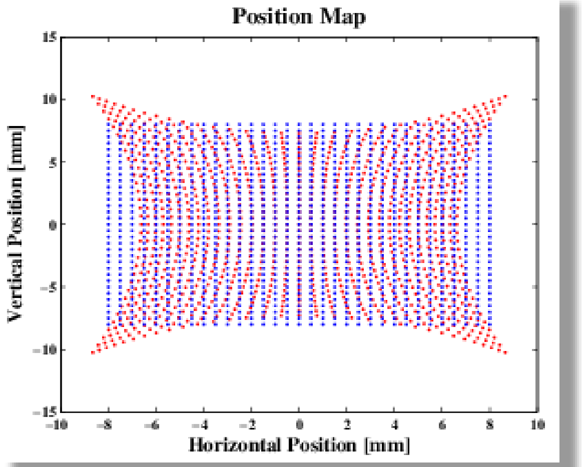
Button BPM feedthrough transmission measurement with reference

Materials and Engineering Technologies for Particle Accelerator Beam Diagnostic Instruments
ARIES

Series Production and Quality Test

The complete system

- In parallel design, production, tests, improvements, commissioning of electronics
- Time for installation including alignment (precision)
- Prepare ADC and FPGA: Server and Firmware
- Not forget cables and their influence to the whole system
- Trigger and synchronization to the beam
- Correction of non-linearities, e.g. tolerances of attenuators, pillow distortion map, I-Q imbalance
- Measurement properties of the system, maybe sorting piecewise
- Calibration of the whole system



Thanks to G. Kube

Ohm-meter

Interconnection plate

Switch-box

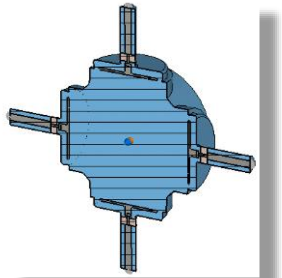
RF generator

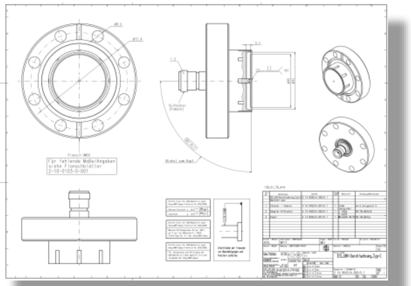
Thanks to B. Roche (ESRF) from DEELS workshop 2018

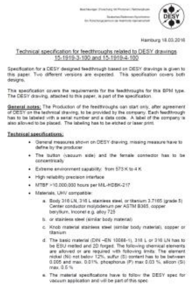
Summary

Example of the development of feedthroughs

Requirements → Simulations and Design → Construction → Discussion with companies → Prototyping







→ Quality Controls → Maybe Redesign → Series production → Quality Controls →

Feedthroughs under test head on

-Vacuum checks
-Cryogenic checks
-Visual checks

Feedthrough transmission measurement with reference (Lab measurements)

-Vacuum checks
-Cryogenic checks
-Visual checks

Sorting → Ready for installation

Summary

Development of diagnostics systems:

- Collect all requirements and conditions; for all necessary sub-systems too: mechanics ↔ electronics
- Simulate design: optimize and tolerance study; mechanical tolerances are not the only sources of performance deviations (brazing, feedthrough, cable, …), talk with companies for feasibility
- Attention to dissipated power, maybe design needs cooling which needs to be implemented in the component
- 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

Thank you for your attention

Do not forget:

- Spare items with respect to MTBF
- Availability of components
- Documentation of each item project phase for reordering

Contact

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