Experience on design, prototyping and testing of cavity BPM for the European-XFEL

- Motivation
- Introduction
- Principle of CBPMs
- Mechanical properties of E-XFEL CBPMs
- Laboratory measurements of series production
- Electronics principle
- Beam based measurements at FLASH1 and FLASH2
- Summary and Outlook

CBPM = Cavity Beam Position Monitors

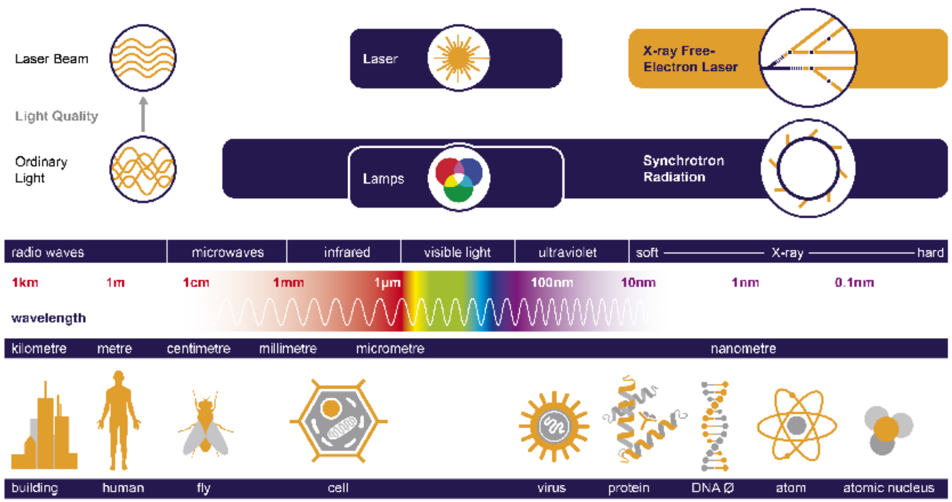
Dirk Lipka for the standard diagnostics team of DESY for E-XFEL
1st PACMAN Workshop
CERN, February 2 – 4, 2015

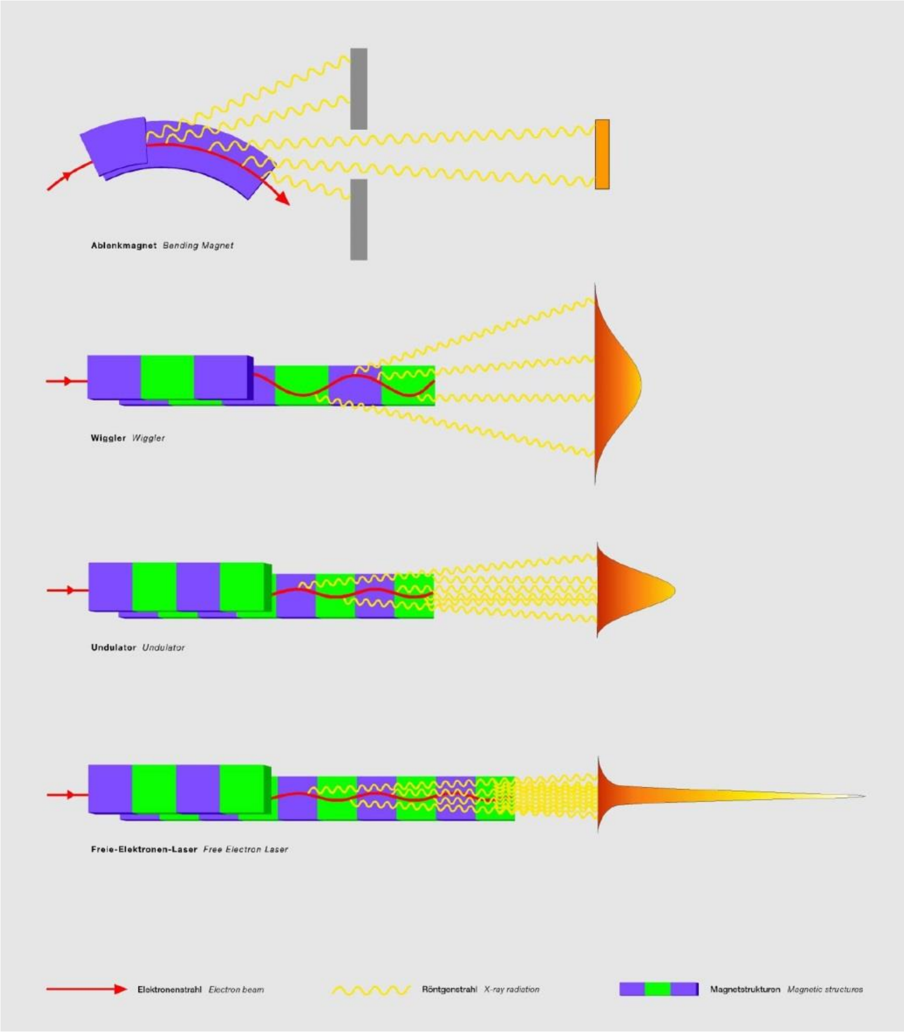
HELMHOLTZ | ASSOCIATION

DESY

Motivation

View inside of structure with photons



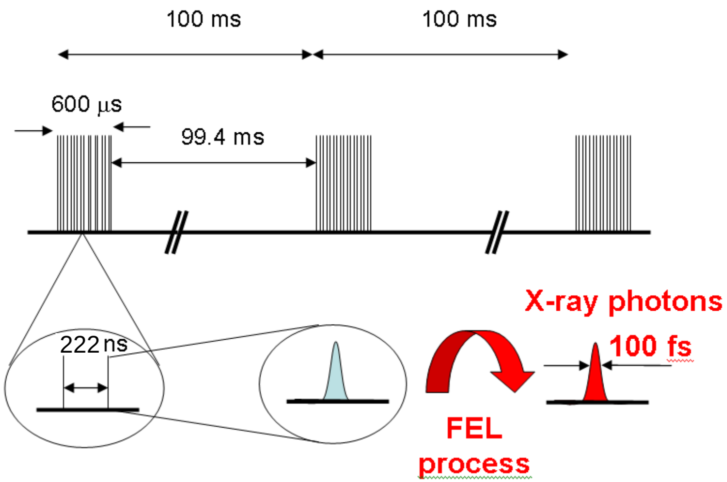


- **>** Shorter wavelength with high intensity resolve smaller structures
- **>** Goal: higher photon energies with high intensity
- **>** Way: Free-Electron Laser (FEL) with undulators

Introduction

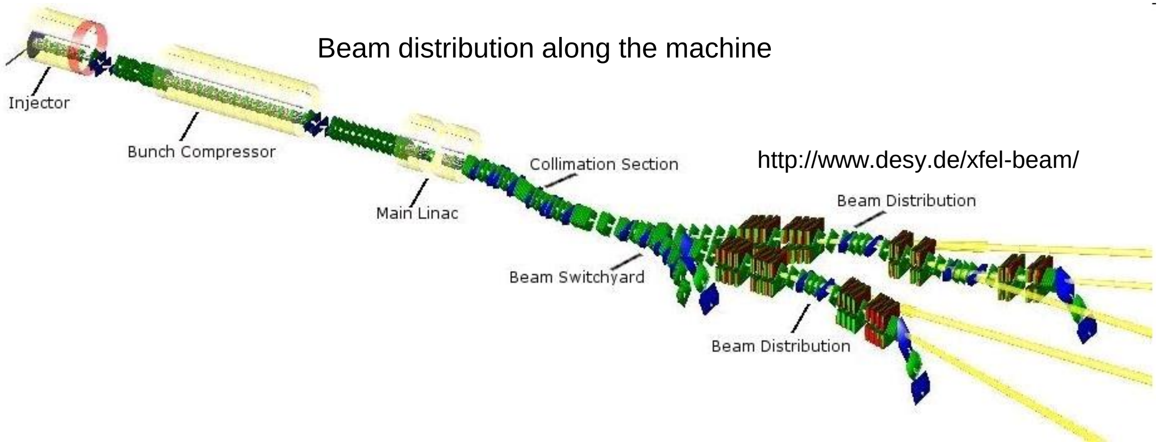
European XFEL status: building-up the most powerful laser with short wavelength

Time structure of bunches



- Strong overlap of electron and photon bunches required
- Transverse size of 30µm expected, need to resolve the positions with lower noise compared to beam size
- Requirement: <1µm BPM noise for charge within 0.1 – 1 nC

Beam distribution along the machine



http://www.desy.de/xfel-beam/

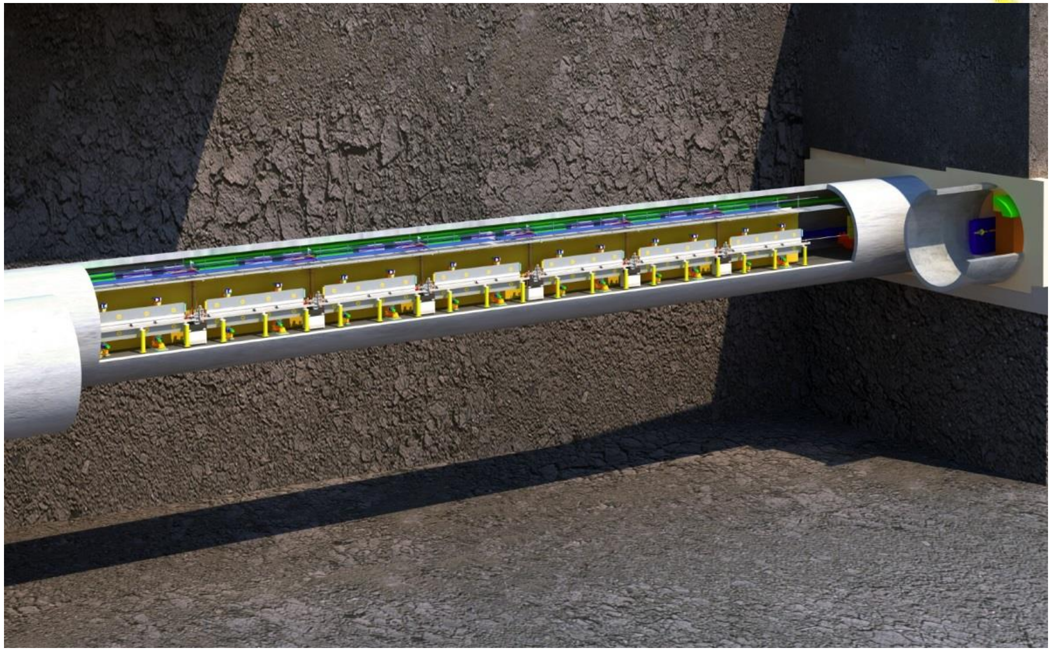


Photo montage of the undulator tunnel https://media.xfel.eu/

Introduction

Cavity BPM for European XFEL within a cooperation:

- DESY: BPM mechanics
- PSI: front end electronics and digitalization

Two kinds of CBPMs designed:

- For undulator intersection with 10mm beam pipe diameter
- For dedicated positions within beamline with high demands on beam position measurements with 40.5 mm pipe diameter, e.g. energy and intra-bunch feedback

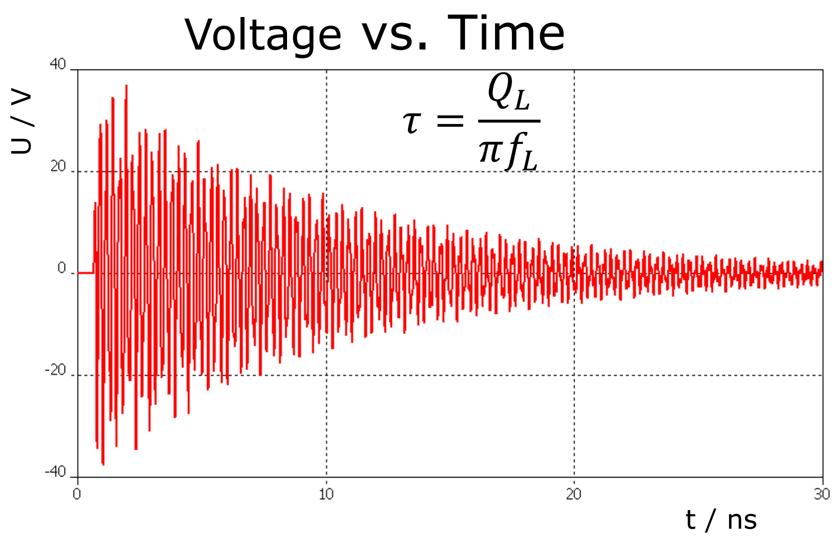
Both kinds have similar properties to use same electronics

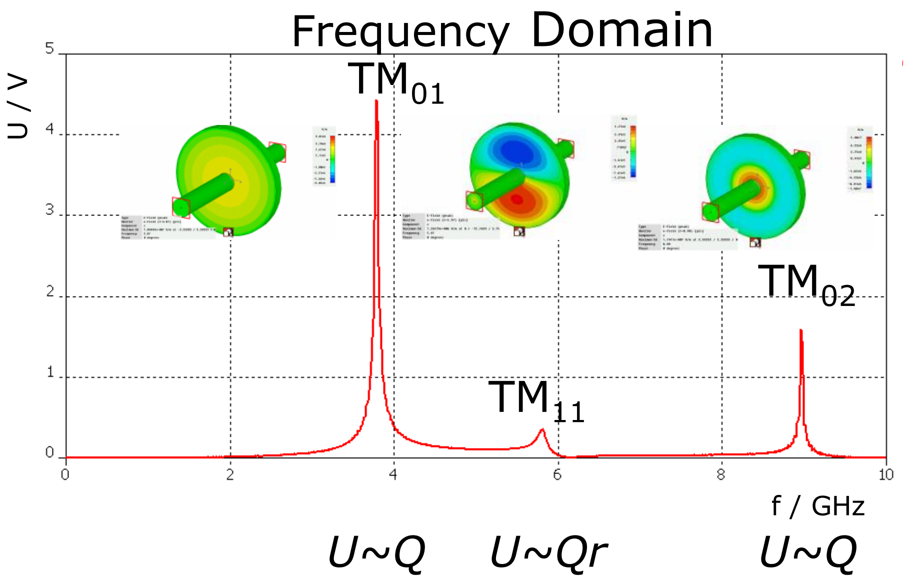
Photos: D. Nölle

Principle of CBPMs

CBPM consists of 2 resonators: dipole for position and reference for normalization

With antenna in resonator following signals can be obtained:

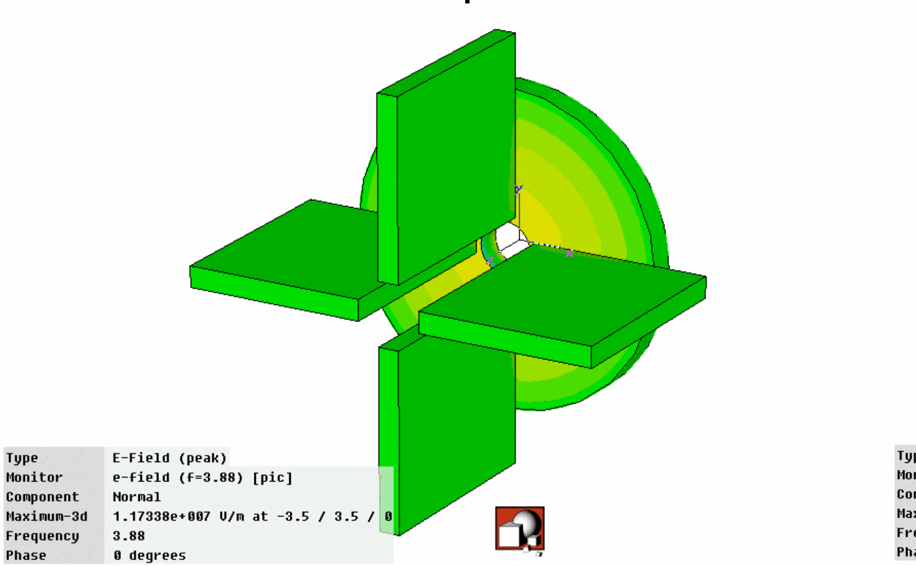




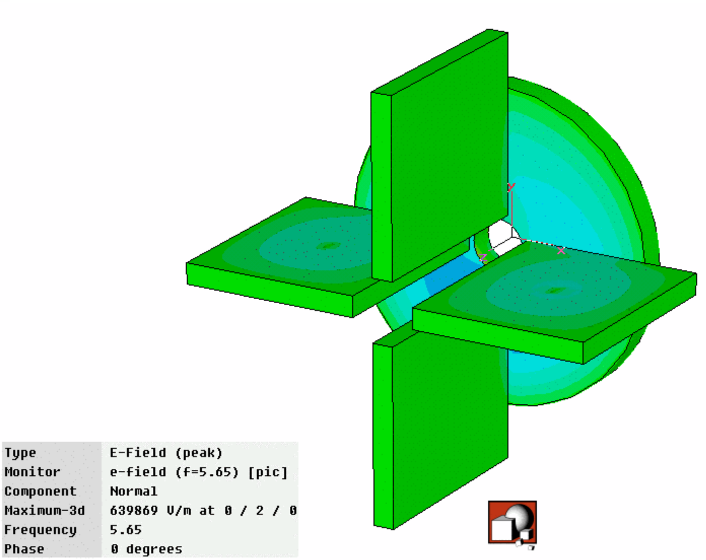
- Amplitude of TM_{11} mode proportional to offset r and charge Q; advantage compared to button or stripline BPMs where two large amplitudes used to calculate small offset
- Waveguide/slot selects dipole mode
- For charge normalization and sign: reference resonator with monopole mode
- Frequencies depend on mechanical sizes; decay time and quality factor depend on material and antenna position

Principle of CBPMs

Monopole Mode



Dipole Mode



Simulation to show

- propagation of dipole mode in waveguide
- monopole mode no propagation in waveguide

Ref: V. Balakin et al., PAC 1999

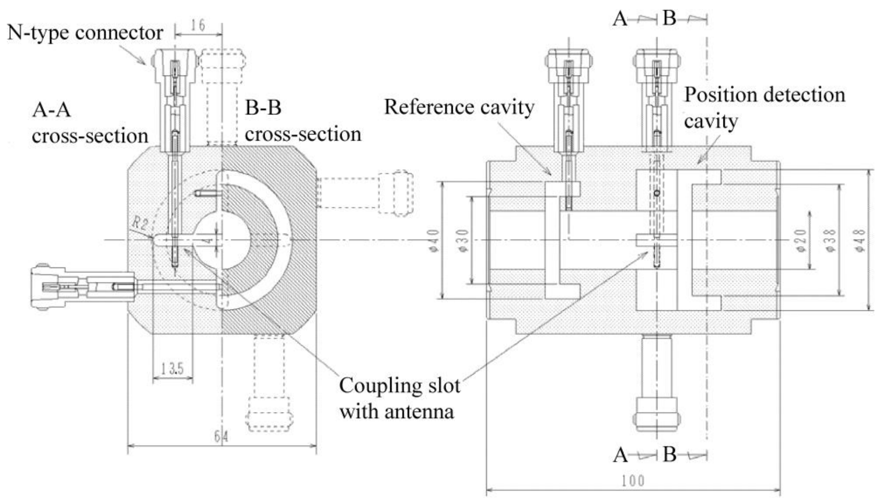
Mechanical properties of E-XFEL CBPMs

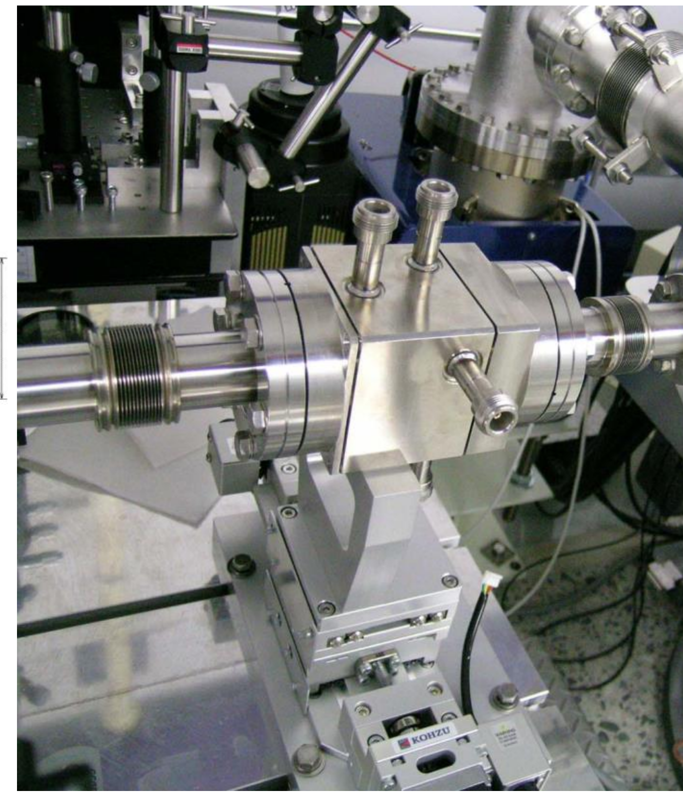
Photo by:

D. Nölle

Design obtained from T. Shintake

His design for SPring-8 Angstrom Compact free electron Laser (SACLA)





- Material: Stainless Steel
- Pipe diam.: 20 mm
- Slots connected to tube

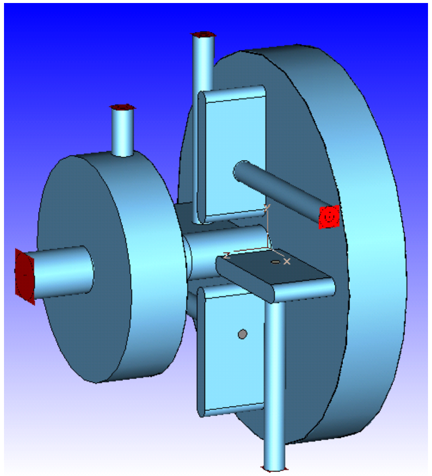
Measured resolution: < 0.6 μm at 0.1 nC

Courtesy H. Maesaka

Mechanical properties of E-XFEL CBPMs

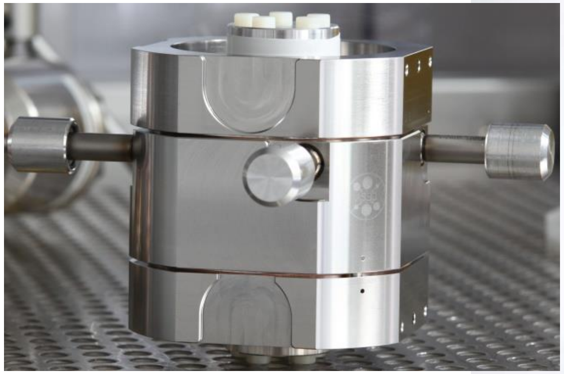
Undulator CBPMs:

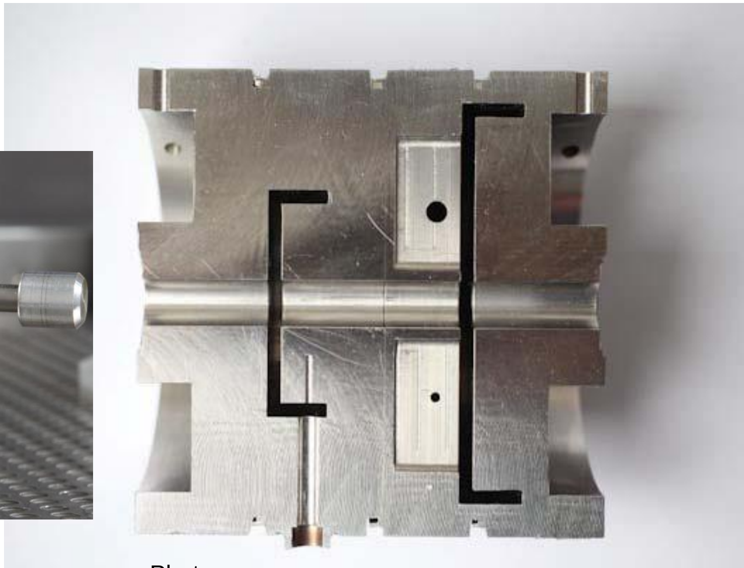
- Stainless steel “discs” forms the cavities without any tuners: RF- properties depend on mechanical tolerances; these tolerances are calculated to match the requirements
- Discs brazed together
- High performance feedthrough welded to the body



Reference and Dipole resonator
Vacuum view

- Resonance frequency (loaded) 3.30 ± 0.03 GHz
- Q, loaded 70 ± 10
- Max. frequency difference between dipole and reference resonator: ≤ 30 MHz
- Crosstalk between resonators: < -100 dB





Photos:
D. Nölle

Q_{loaded} results in decay time of 6.7 ns to be able to resolve bunches with 222 ns distances

Mechanical properties of E-XFEL CBPMs

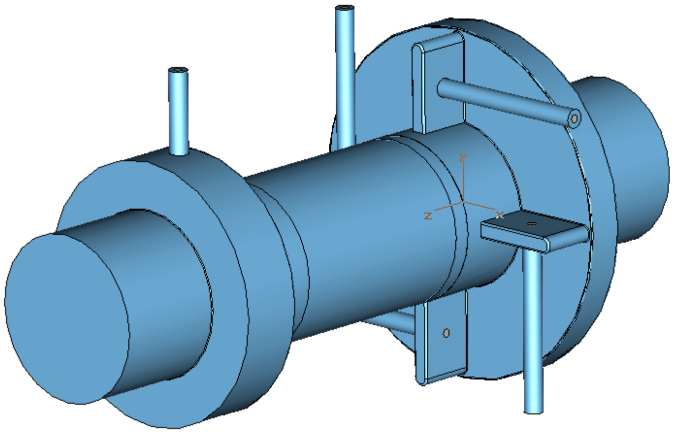
Beamline CBPMs:

- Stainless steel “discs” form the cavities without tuners
- Brazed together
- Distance between reference and dipole resonator = 190 mm
- High performance feedthrough flange mounted

- Frequency (loaded) 3.3 ± 0.03 GHz
- Q, loaded 70 ± 10
- Frequency difference between dipole and reference resonator: ≤ 30 MHz
- Crosstalk between both resonators: < -100 dB

Q_{loaded} results in decay time of 6.7 ns to be able to resolve bunches with 222 ns distances

Coupling between both resonators (defines distance): < -100dB



Reference and Dipole resonator

Vacuum view

Photo: D. Nölle

Laboratory measurements of series production

> Statistics after production of 122 Undulator Cavity BPMs

Dipole resonator	3295.4 ± 1.6 MHz 69.3 ± 1.1
Reference resonator	3301.3 ± 5.4 MHz 75.5 ± 1.2
Resonance frequency difference	6.4 ± 4.7 MHz

Resonance frequency and loaded quality factor

Errors are standard deviation

Photo: D. Lipka

6 Undulator BPM in a transport box

- Larger deviation of reference frequency due to brazing problem
- After correction of brazing foil this effect disappears
- Good communications between DESY and company to solve problems
- RF-properties of all BPMs within specifications
- Production according to planning; finished July 2013

Laboratory measurements of series production

- Statistics after production of 30 Beamline Cavity BPMs

Dipole resonator	3295.1 ± 1.3 MHz 87.6 ± 1.9
Reference resonator	3298.9 ± 2.4 MHz 54.3 ± 2.4
Resonance frequency difference	3.9 ± 2.1 MHz

Resonance frequency and loaded quality factor

Errors are standard deviation

Picture by D. Nölle

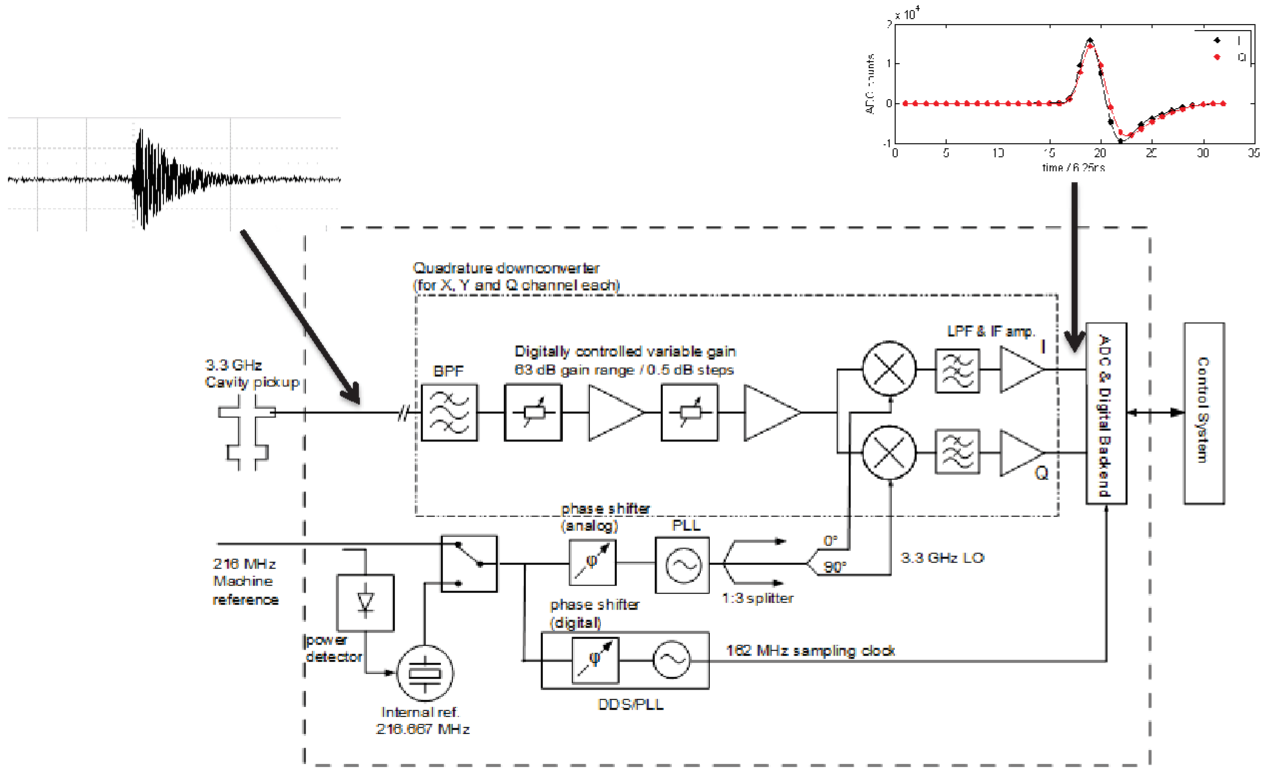
- Frequencies match better to specification compared to Undulator Cavity BPM
- Loaded quality factor shift observed: higher for dipole and lower for reference resonator; reason not understood; electronics can cope with the difference
- Good communications between DESY and company to solve problems
- Production within proposed time duration; finished similar to Undulator production in July 2013

Electronics principle

- Each of all 3 channels similar electronics
- One machine reference for all 3 channels
- Amplitude detection because of short bunch distance (low quality factor) compared to machines with low bunch repetition rates
- Corrections: IQ imbalance, attenuator values, beam angle, scaling to physical values, BPM rotation

• Single stage quadrature downconversion to (≈zero)-IF
• Sampling using 16-bit / 160MSPS ADC
• RF & sampling phase adjustable

Provided by Markus Stadler, PSI

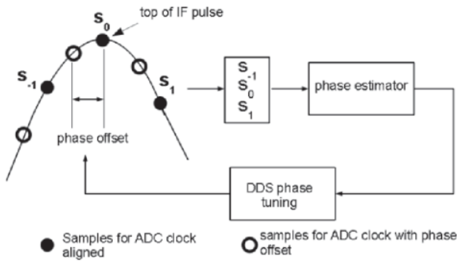


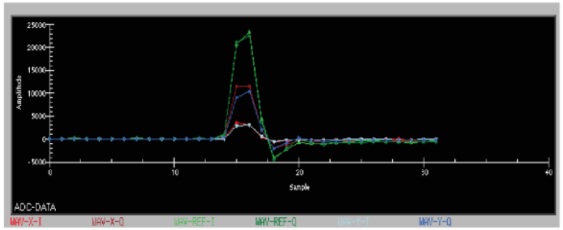
Electronics principle

Provided by Markus Stadler, PSI

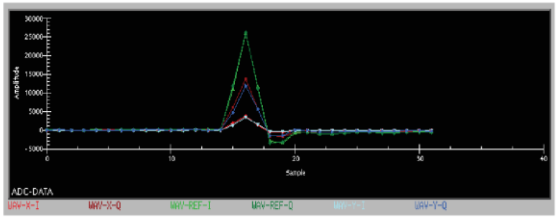
Compensating Signal Phase Drift

- Bunch-synchronous 216.66 MHz reference signal may drift away
- Sampling phase is digitally controlled to align the pulse top
- RF phase is digitally aligned to a 45 degrees angle of the reference cavity signal



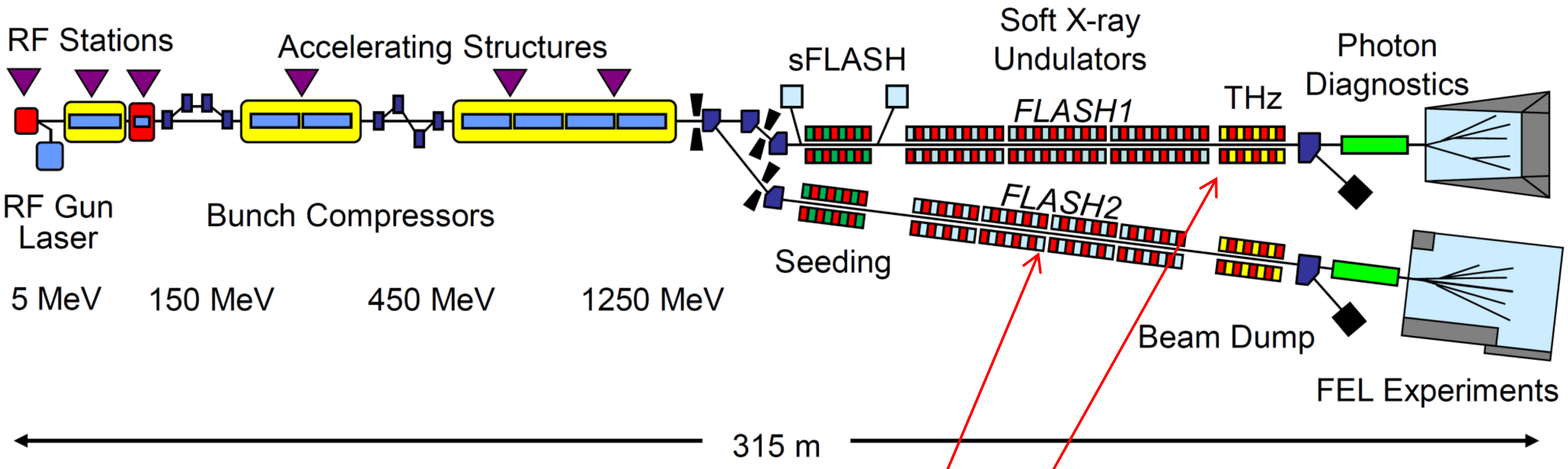


Sampler not aligned (phase≠0)

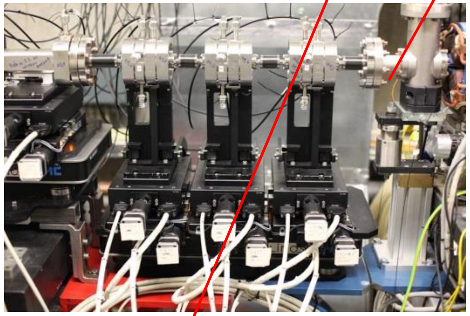


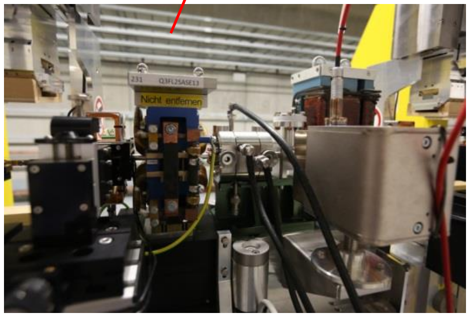
Sampler aligned (phase=0)

Beam based measurements at FLASH1 and FLASH2



Free-Electron Laser in Hamburg (FLASH) user facility with possibilities of testing new components





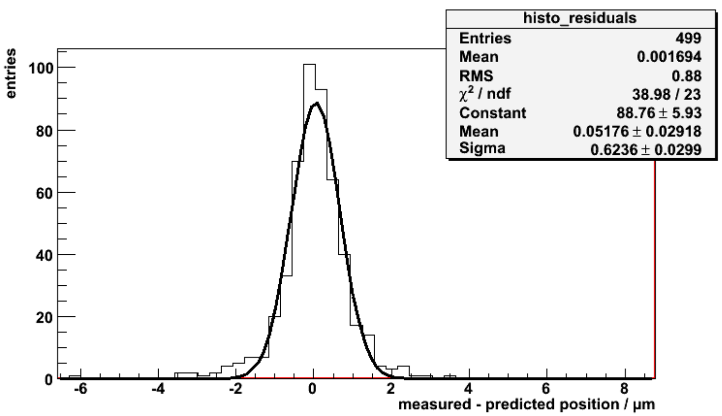
Photos:

D. Nölle

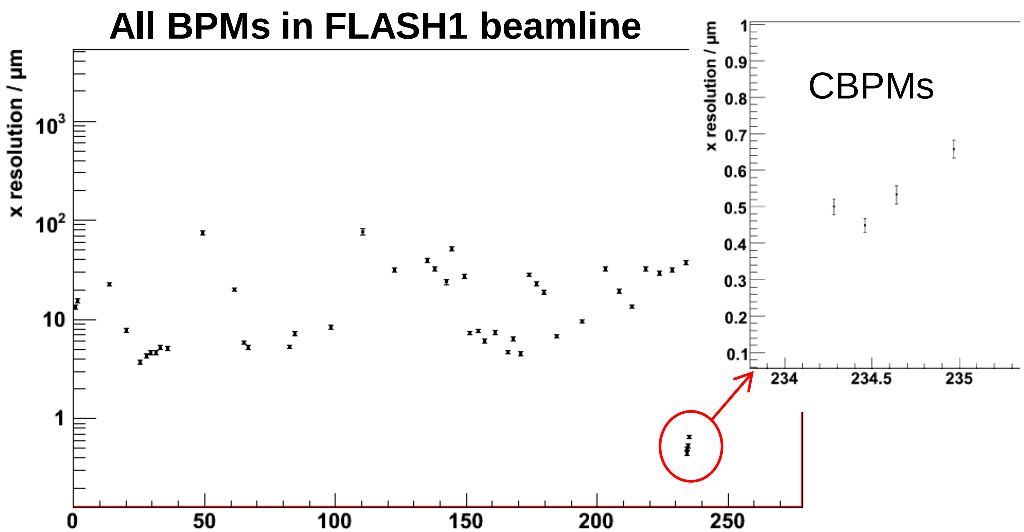
- Teststand at FLASH1 installed with 3 undulator and 1 beamline CBPM
- 17 undulator CBPM installed in FLASH2 2014
- Commissioning with electronics prototypes in both machines

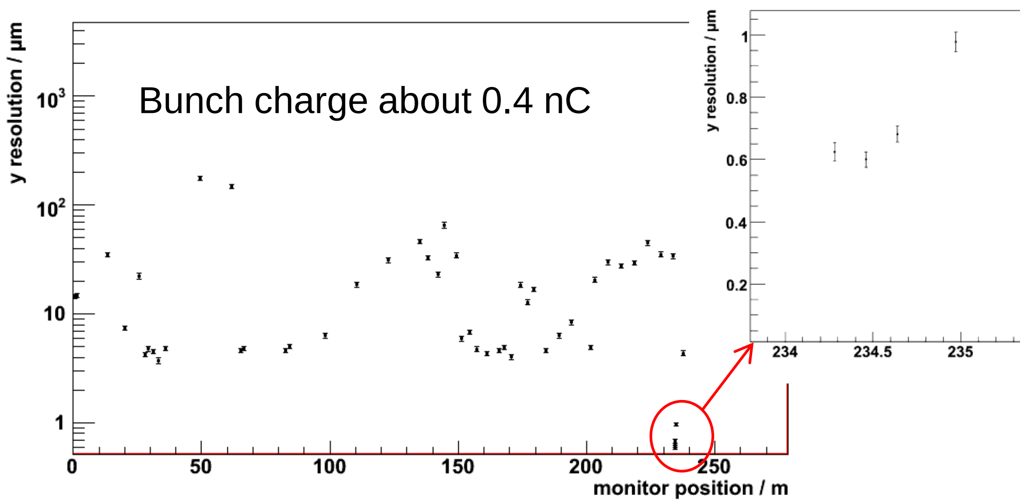
Beam based measurements at FLASH1

- Measurement of all BPM position along FLASH to FLASH1 beamline
- Using all BPM except one under test and predict the position for each bunch to this BPM
- calculate difference between prediction and measurement results in BPM noise



- The electronics preliminary mode noise undergo requirement for E-XFEL
- Similar for bunch charge measurement

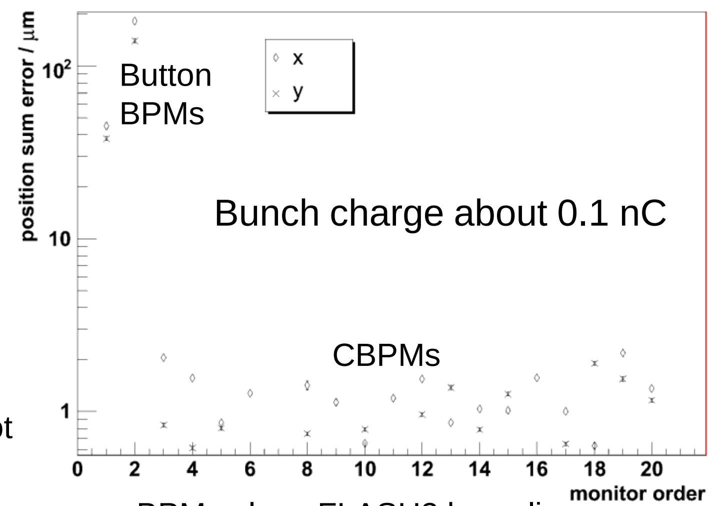




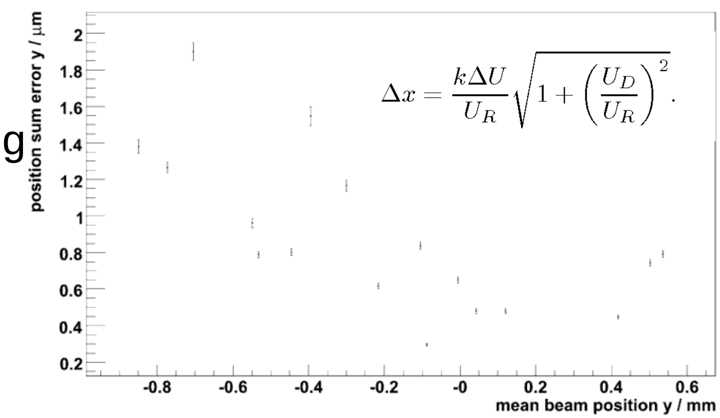
Beam based measurements at FLASH2

- Laboratory calibration provided; BPM output already visible at commissioning of FLASH2 including lab calibration
- All CBPMs and 2 Button BPMs are used at FLASH2 to calculate difference of BPM under test to the others
- Compared to FLASH1 larger noise value, reasons:
  - Frequent changes of attenuators due to larger offsets
  - ADC may saturate with large amplitudes indicated via valid flag but not yet integrated in control system
  - Mechanical vibrations
- Noise value depends on offsets due to amplitude, two attenuator setting visible
- More detailed analysis of individual contributions ongoing
- Beam based calibration ongoing

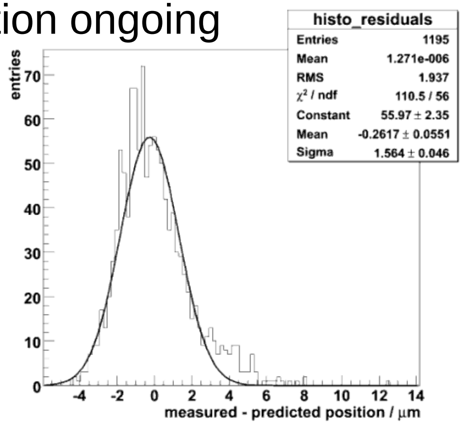
All CBPMs in FLASH2 beamline



BPMs along FLASH2 beamline



Noise of CBPMs as a function of beam position



Summary and Outlook

Summary:

- Description of E-XFEL
- Principle of CBPMs
- Properties of CBPMs for E-XFEL
- Laboratory and beam based measurements

Outlook:

- Beam based calibration with one steerer and beamline lattice at FLASH2 and improvements on noise ongoing
- Building-up beamline of E-XFEL started in 2014, will end 2016
- Alignment of undulator intersection with about 300 µm precision
- Beam based fine alignment with CBPMs: measure beam offset with straight beam trajectory, in the tunnel readjust holder and measure again -> straight electron beam trajectory through center of quadrupoles

Undulator intersection design