High resolution cavity BPMs in the context of the European XFEL

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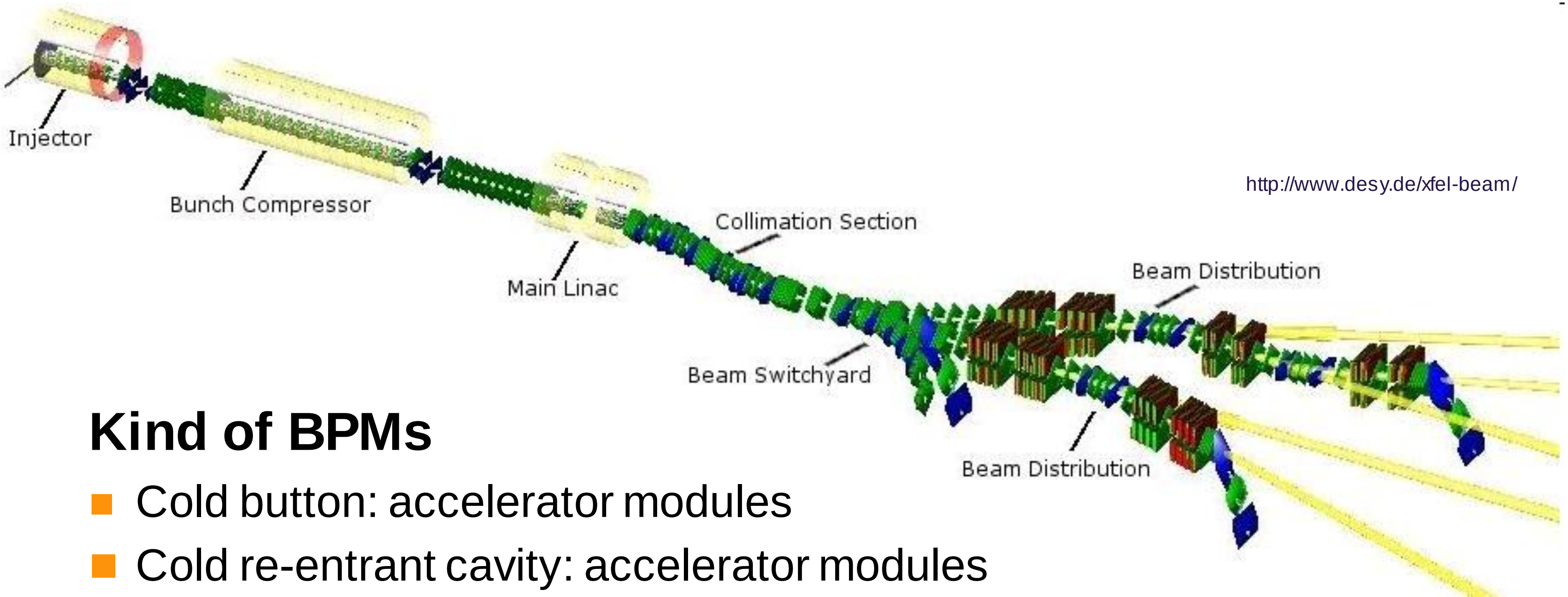
Overview



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

Kind of BPMs

- Cold button: accelerator modules
- Cold re-entrant cavity: accelerator modules
- Warm button: distribution system, compressors
- Beamline cavity (14): intra bunch feedback system (IBFB), matching
- Undulator cavity (117): undulator

In Kind Contribution

All BPM for European XFEL (cold and warm)

Collaboration (institutes and task)

- Saclay: re-entrant cavity BPM for cold module including front end electronics
- DESY: button and cavity BPM mechanics
- PSI: front end electronics (button and cavity BPM) and digitalization (all): see talk B. Keil

Subject of this talk:

Cavity BPM from DESY

Photo: D. Nölle

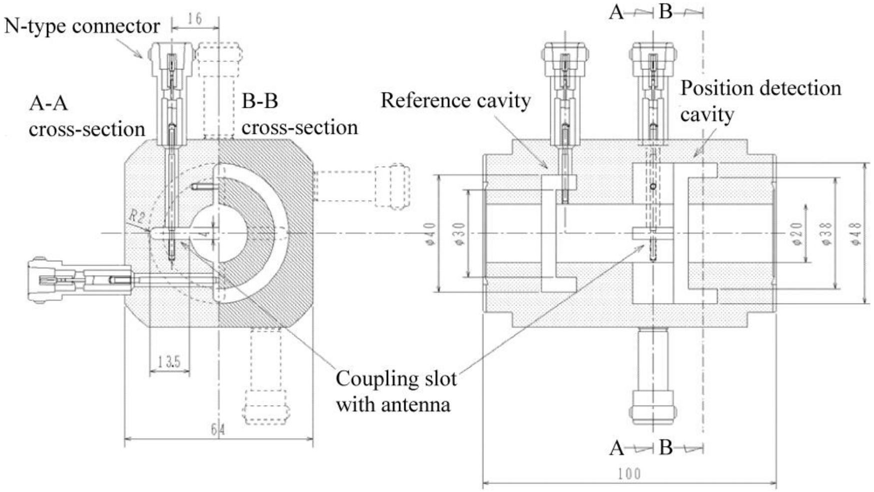
Basis

Photo by:

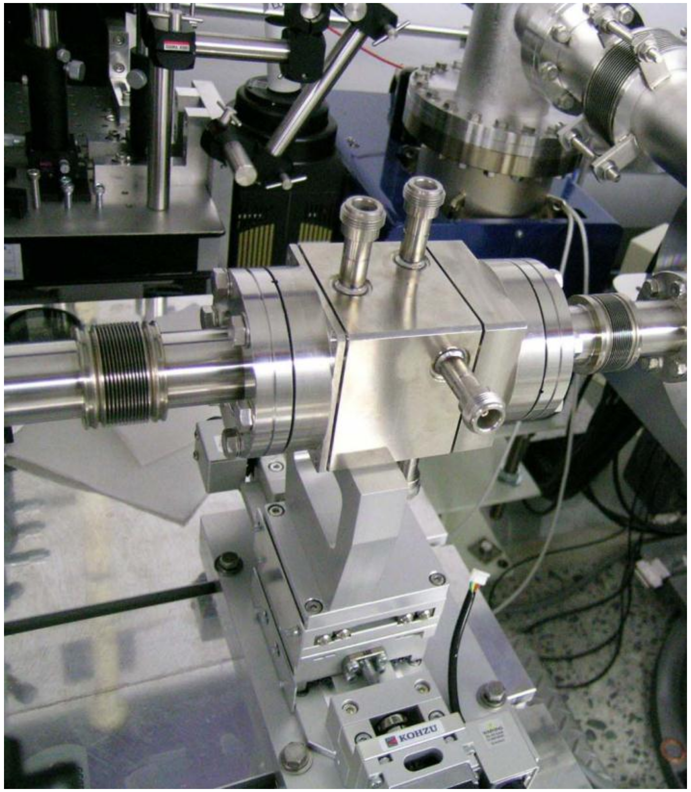
D. Nölle

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: < 0.2 µm

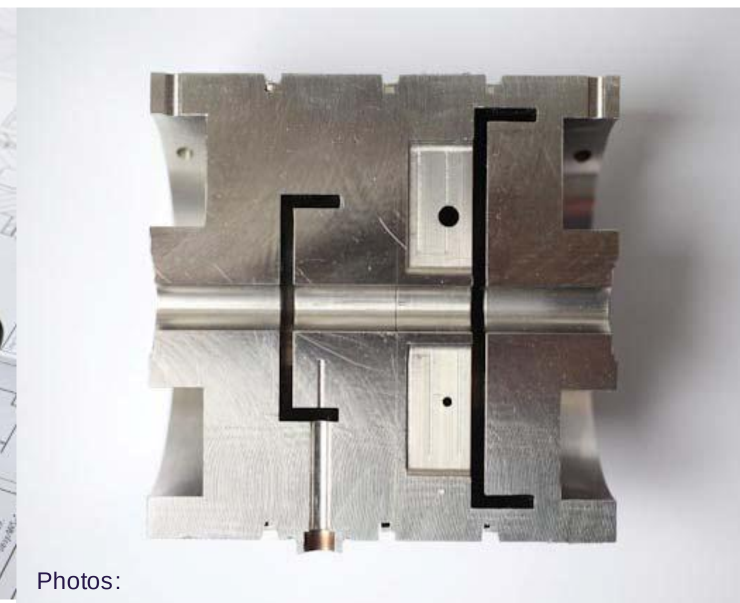
Courtesy H. Maesaka

European XFEL

Design for E-XFEL: undulator cavity BPM

- Stainless steel discs forms the cavities without tuners
- Slots without direct connection to tube
- Braced together
- High performance feedthrough welded on body

- **Resonance frequency** (loaded) 3.30 ± 0.03 GHz
- **Q, loaded** 70 ± 10



Photos: D. Nölle

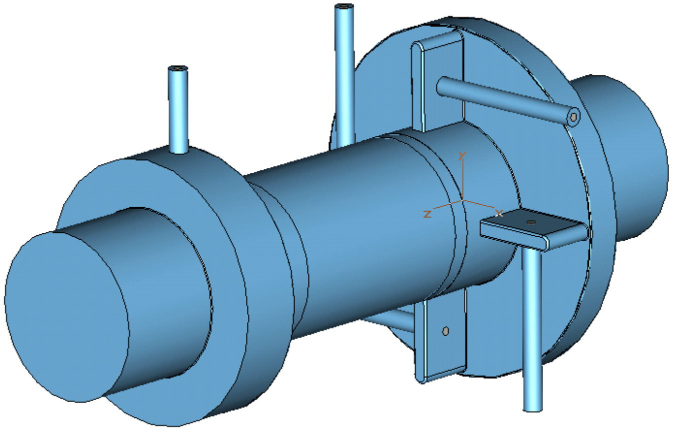
European XFEL

Design for E-XFEL: beamline cavity BPM

- Stainless steel discs forms the cavities without tuners
- Slots with direct connection to tube
- Braced together
- Distance between reference and dipole resonator = 190 mm
- High performance feedthrough flange mounted

Frequency (loaded)	3.3 GHz
Q, loaded	70

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



Reference and Dipole resonator

Vacuum view

Photo: D. Nölle

DESY HELMHOLTZ ASSOCIATION

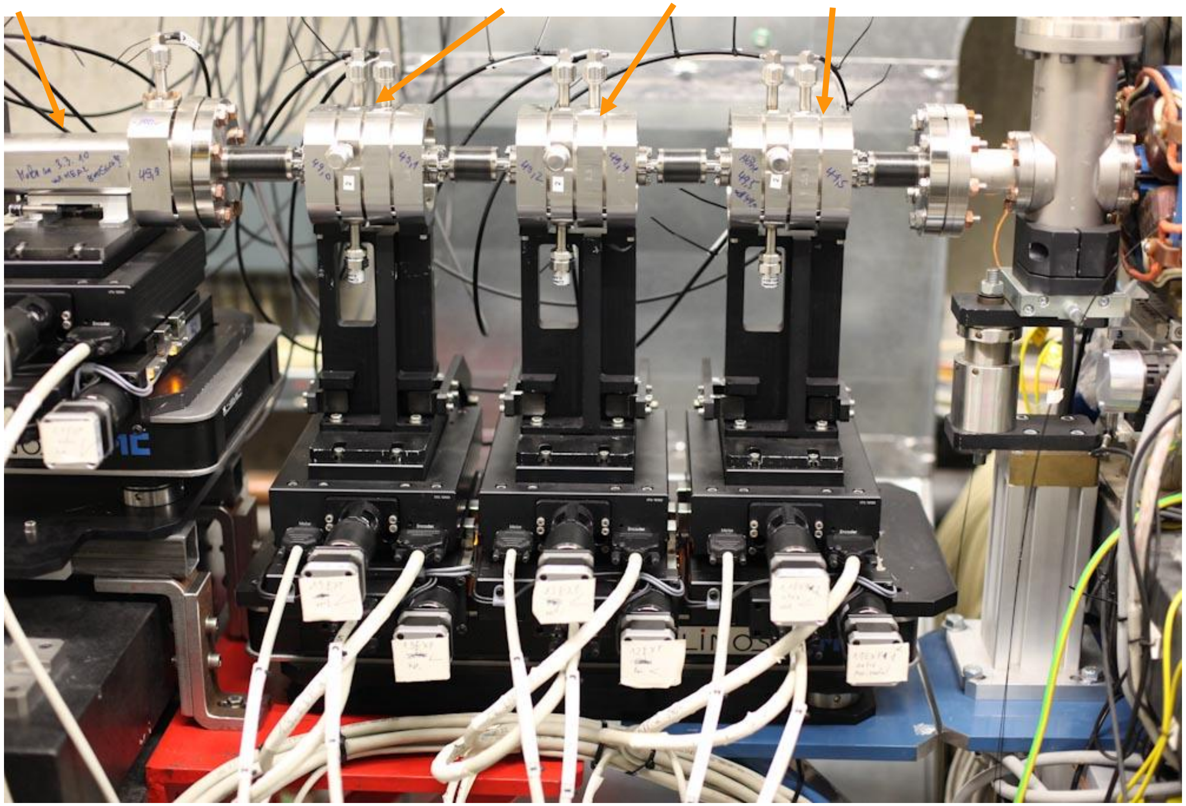
Measurement at FLASH: BPM test stand

Beamline cavity BPM

Notation: 2.1

Undulator cavity BPMs:

1.3 1.2 1.1



Beam

After last SASE undulator

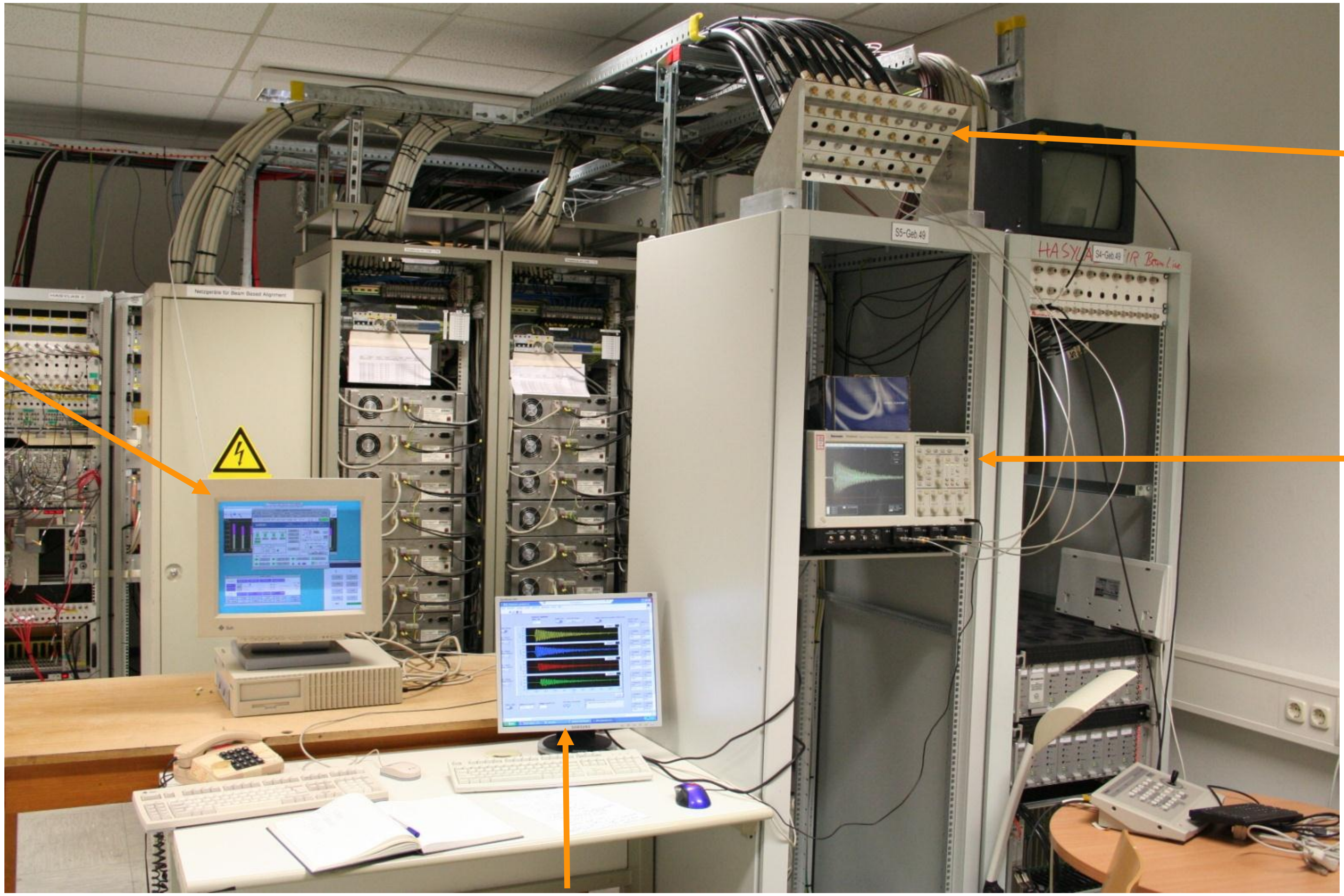
Photo: D. Nölle

- Three Undulator cavity BPMs with tube diameter 10 mm
- One Beamline cavity BPM with tube diameter 40.5 mm

European XFEL

Setup in Rack room

FLASH control system display



End of cables from tunnel

oscilloscope

DAQ

Measurement with oscilloscope in summer 2010. PSI electronics in development (see talk by B. Keil). 4 channels available for 4 BPMs.

Reference resonator Undulator type

Connectors for reference resonator

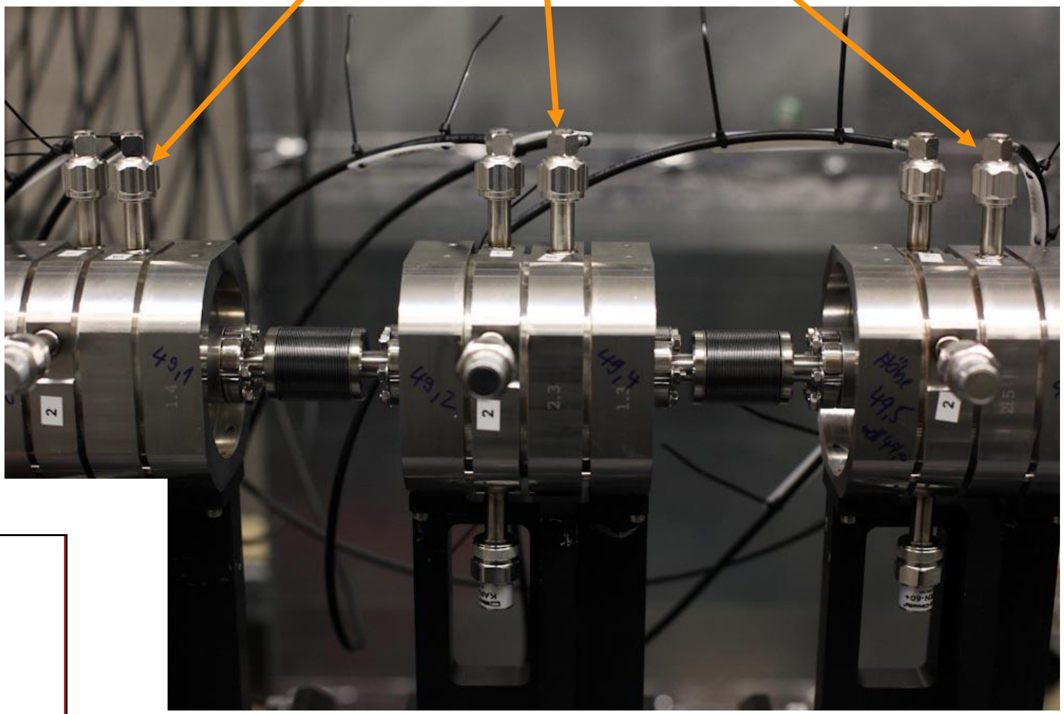
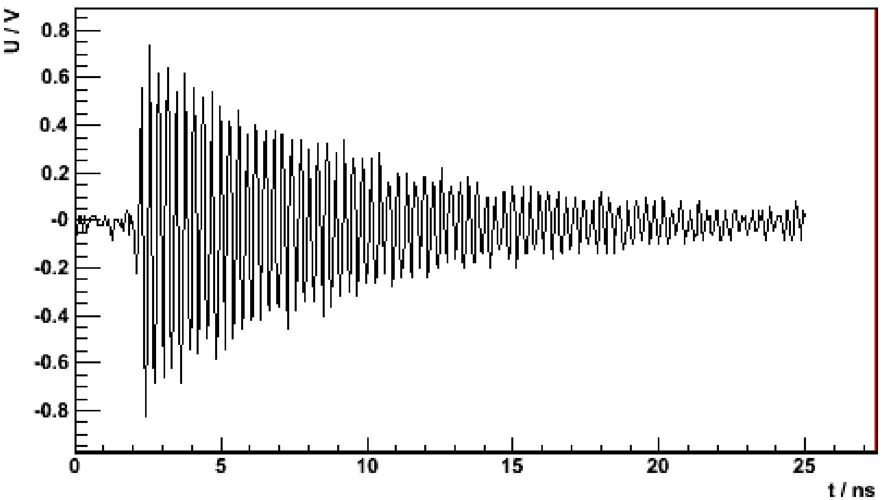


Photo:
D. Nölle

Reference resonator in each BPM for phase and charge calibration



Signal at rack room without corrections (attenuation of cables and filter)

Reference resonator Beamline type

Beamline Cavity BPM
 proposed to use at critical positions at E-XFEL with larger beam tube diameter (compared to the undulator type)

Connector for reference resonator

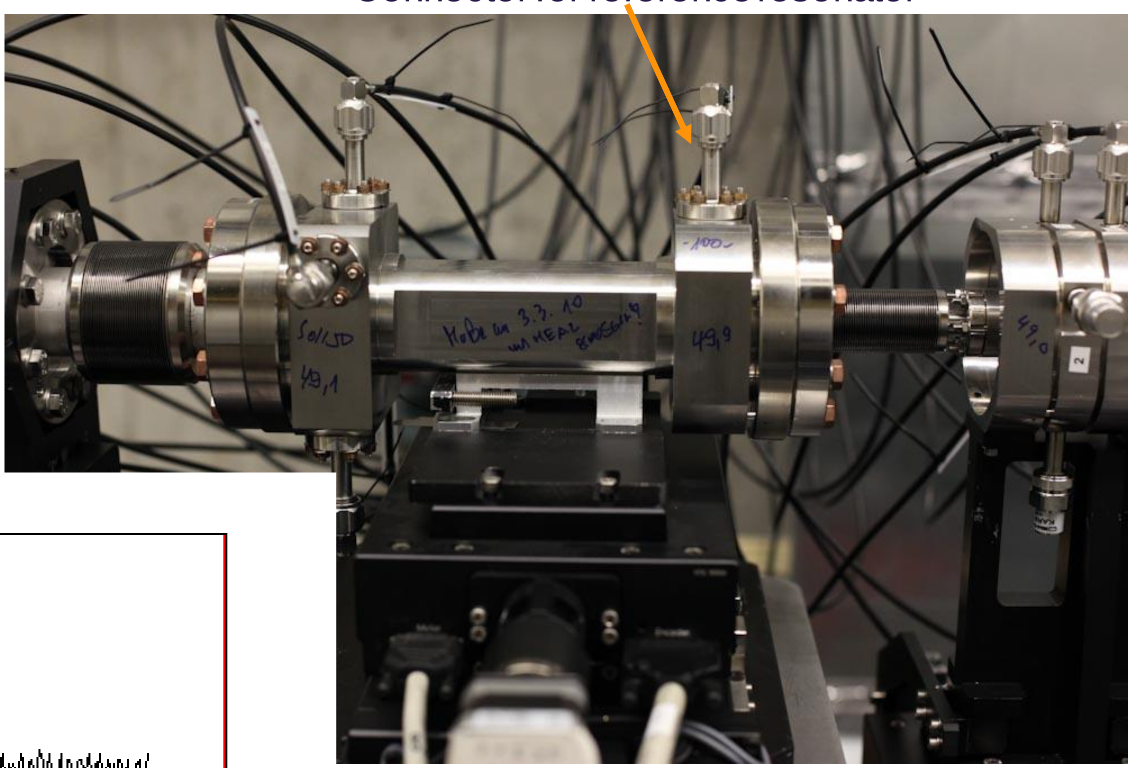
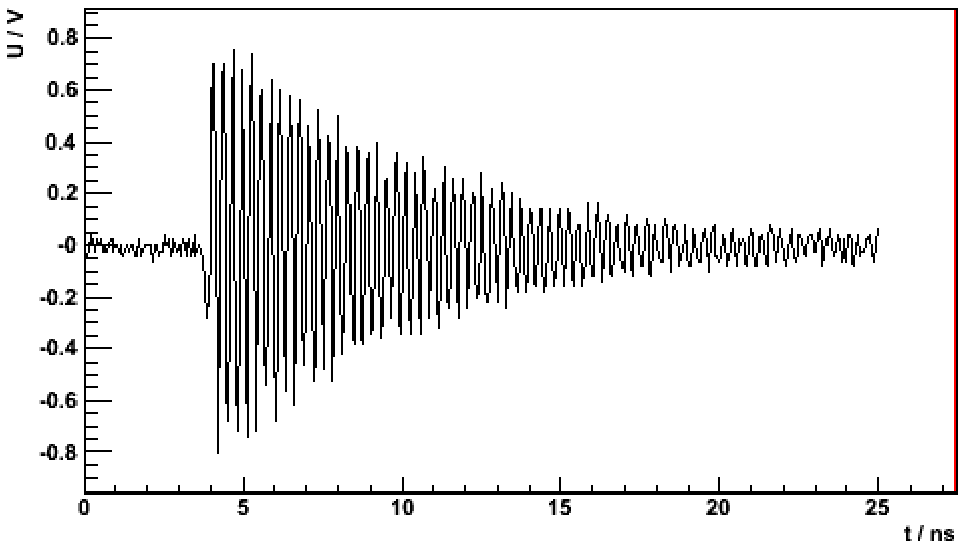


Photo: D. Nölle



Signal at rack room without
 corrections (attenuation of cables and filter)

Beam measurement of Undulator cavity BPM

Analysis: To increase oscilloscope resolution for amplitude a fit is applied to the time signal, in addition resonance frequency and loaded quality factor is observed:

$$U(t) = U_{out} e^{-\frac{t-t_s}{\tau}} \cos(\omega_R t + \phi)\Theta(t_{trigger} + t_s)$$

$$\omega_R = 2\pi f_R$$

f_R *resonance frequency*

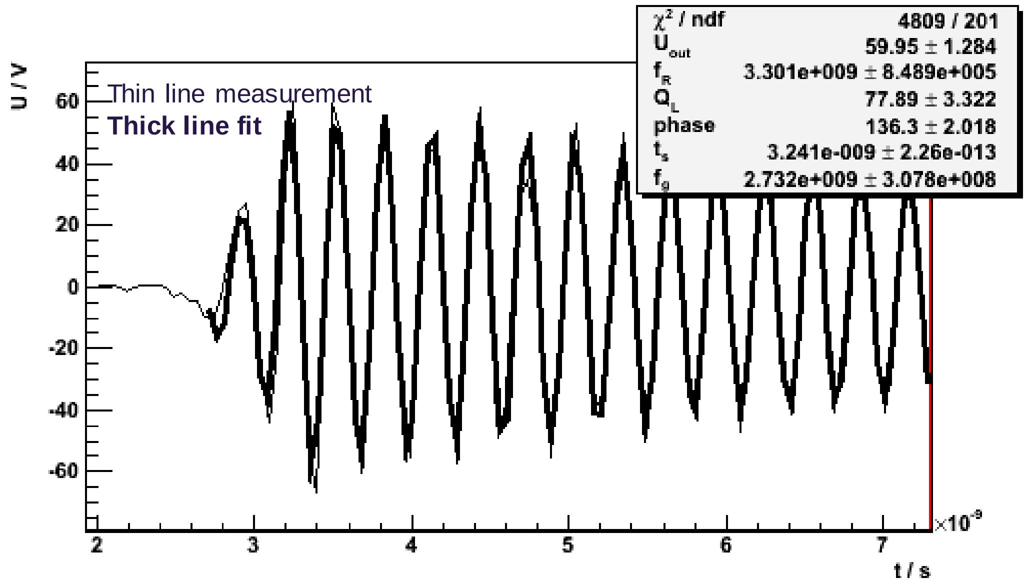
$$\tau = \frac{Q_L}{\pi f_R}, \text{ decay time}$$

Q_L *loaded quality factor*

$U_{out} \propto$ *beam offset*

ϕ *phase offset*

t_s *end of transient oscillation*

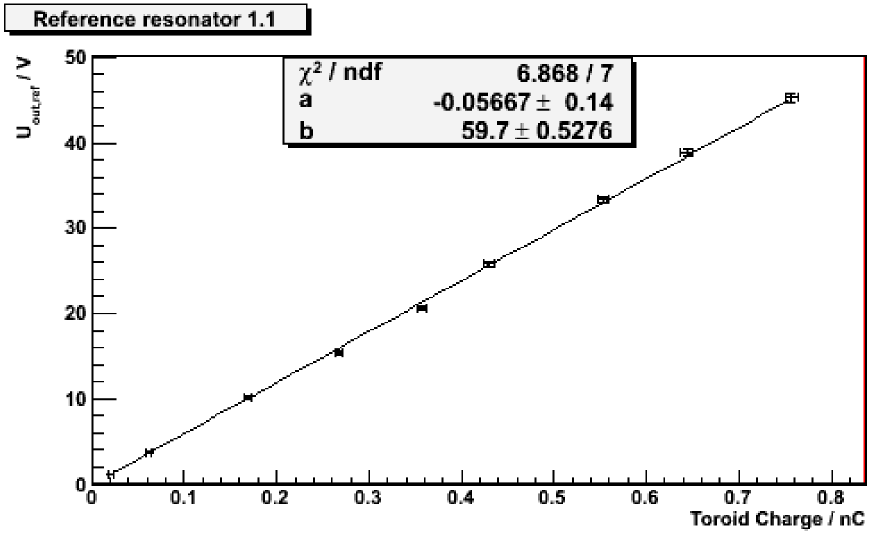


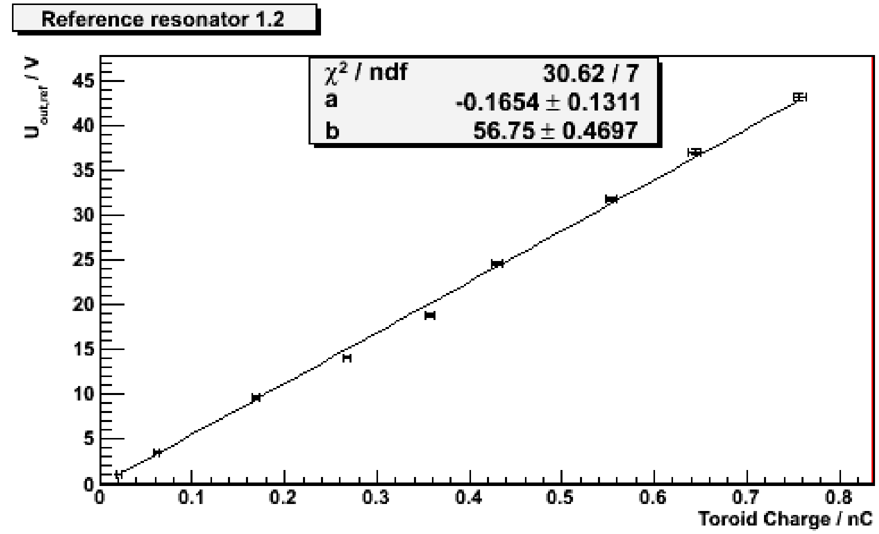
For time between $t_{trigger}$ and t_s (transient oscillation):

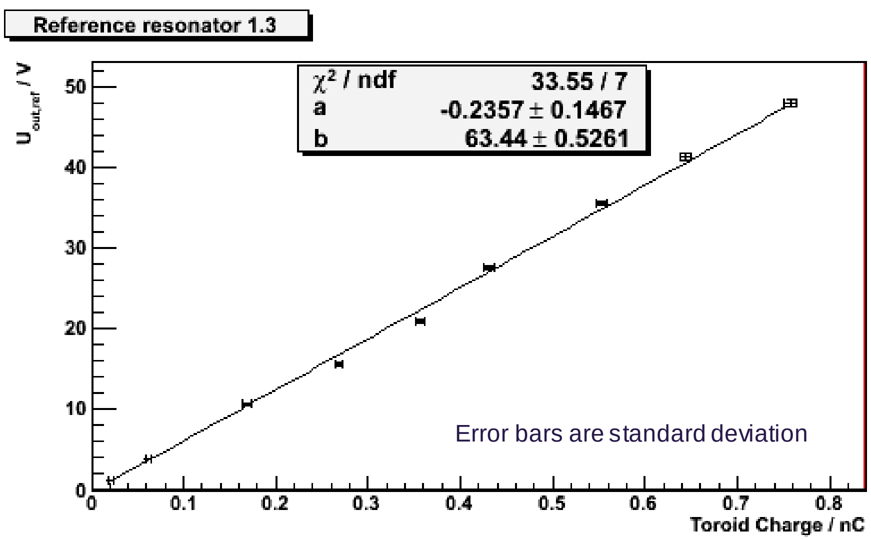
$$U(t) = U_{out} e^{(t-t_s) f_g} \cos(\omega_R t + \phi)$$

f_g *gradient frequency*

Reference resonator Undulator type







Error bars are standard deviation

<u>Amplitude as a function of next Toroid</u>

4 Oscilloscope channels used with 4 Cavity BPMs

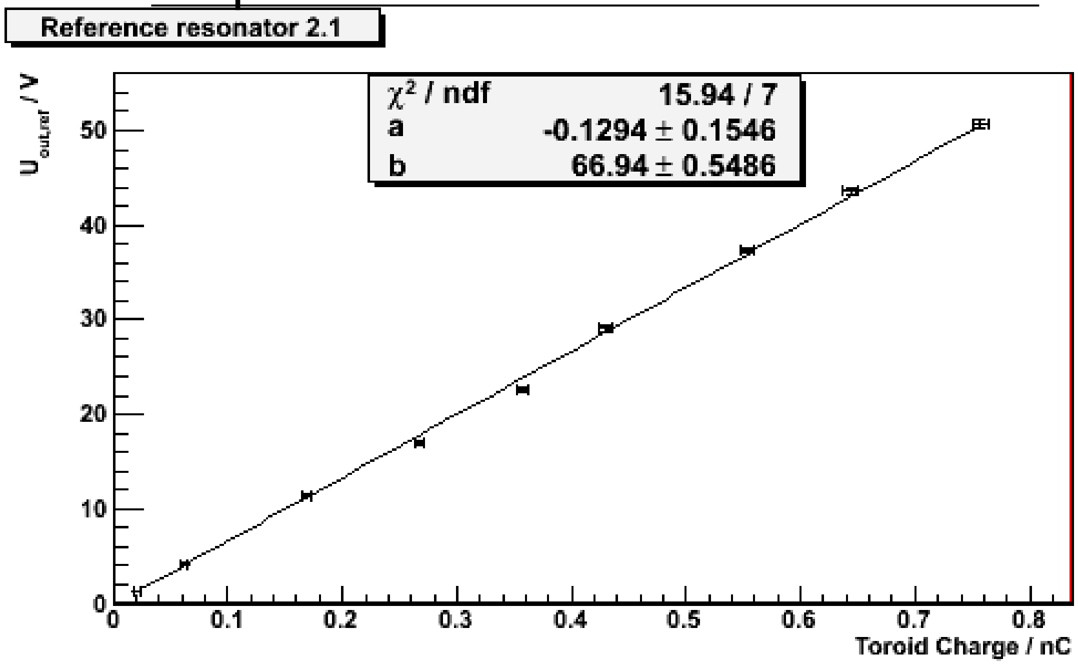
Signal from BPM is corrected with attenuation of cables, attenuators and filters.

Slope b is sensitivity, important for electronics development

Expected: 43.5 V/nC

Reference resonator Beamline type

Amplitude as a function of next Toroid



Last channel of the oscilloscope connected to the Beamline type Cavity BPM

Sensitivity is comparable with undulator type, same electronics can be used for both types

Expected: 42.9 V/nC

Sensitivity higher as expected

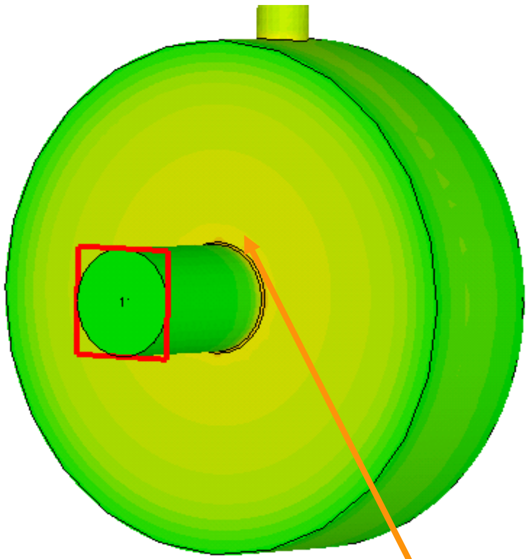
Reason of difference between measurement and expectation

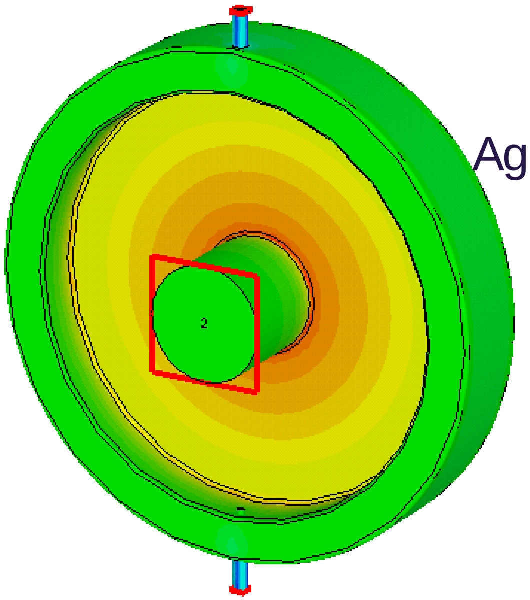
Simulation view of reference resonator with

one antenna

two antennas

Disagreement between measurement and simulation





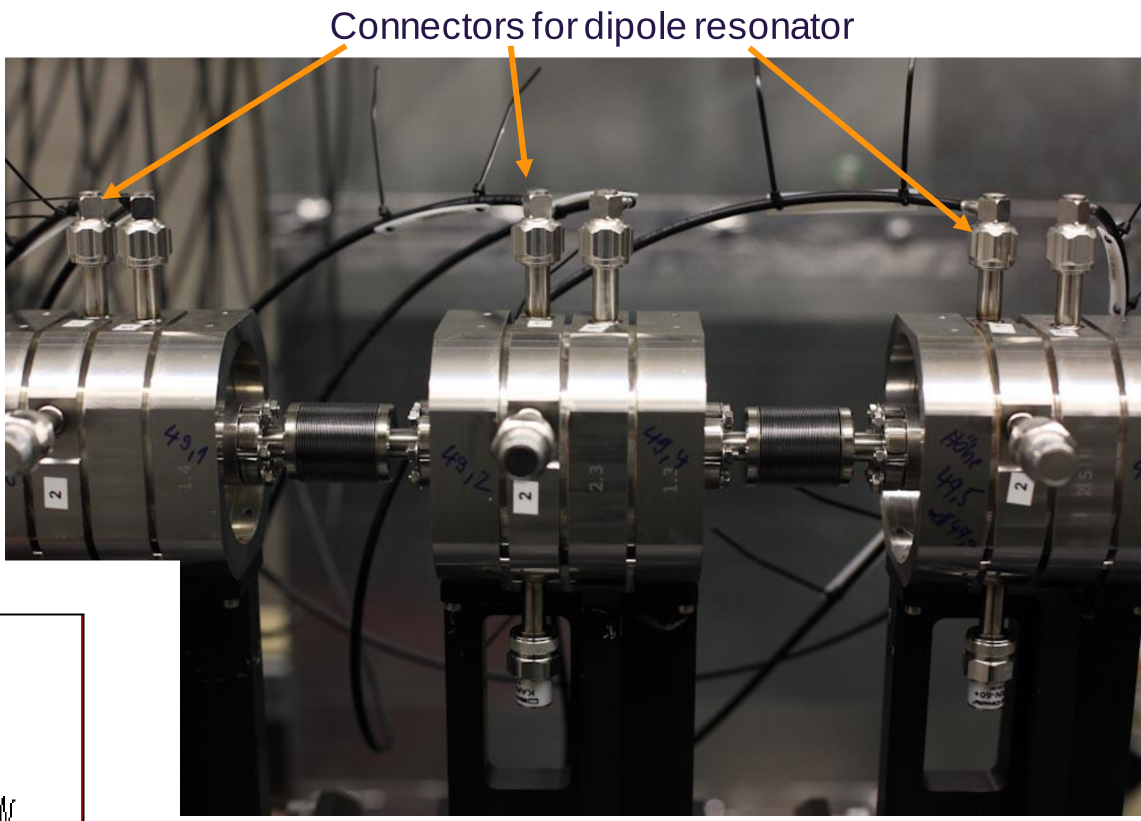
Agreement between measurement and simulation

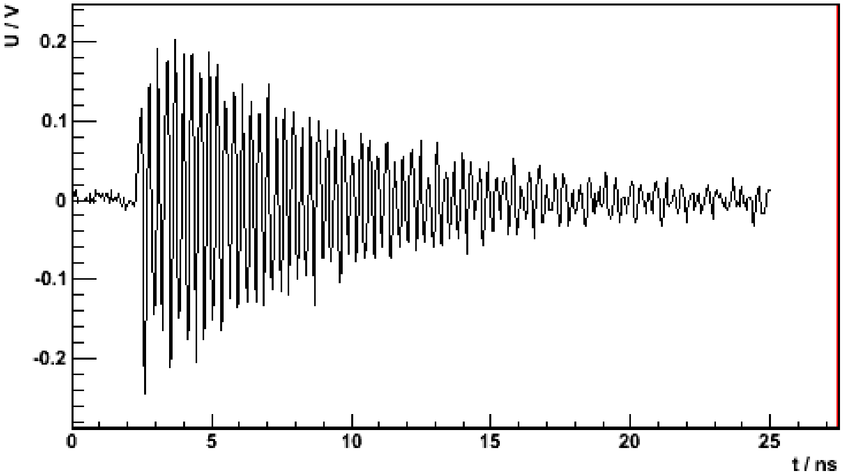
Field distribution due to antenna distorted, difficult to simulate because no symmetry

But: a vacuum RF feedthrough is expensive. Therefore one antenna for the reference resonator.

Dipole resonator signal from undulator type

Dipole resonator signal proportional to charge and offset



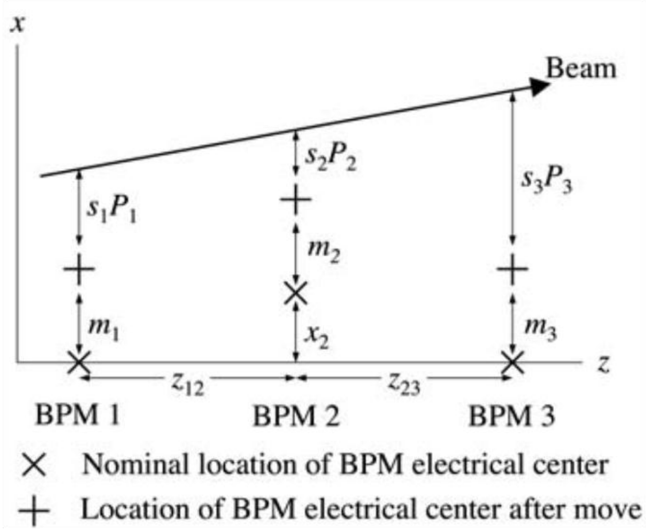


Signal at rack room without corrections, amplitude smaller compared to reference signal because of different field mode

Photo: D. Nölle

Dipole resonator signal calibration theory

Ref: S. Walston et al., Performance of a High Resolution Cavity Beam Position Monitor, 2007



$$\frac{(m_2+x_2+s_2P_2)-(m_1+s_1P_1)}{z_{12}} = \frac{(m_3+s_3P_3)-(m_2+x_2+s_2P_2)}{z_{23}},$$

With $1/s_i$ is sensitivity (which we want to measure), m_i is mover position, P_i is amplitude of dipole resonator and x_2 is an unknown offset

Reordering equation such that s_i and x_2 in a vector:

$$-\frac{m_1}{z_{12}}+\left(\frac{1}{z_{12}}+\frac{1}{z_{23}}\right)m_2-\frac{m_3}{z_{23}} = \begin{pmatrix} \dfrac{P_1}{z_{12}} \\ -\left(\dfrac{1}{z_{12}}+\dfrac{1}{z_{23}}\right)P_2 \\ \dfrac{P_3}{z_{23}} \\ -\left(\dfrac{1}{z_{12}}+\dfrac{1}{z_{23}}\right) \end{pmatrix} \cdot \begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ x_2 \end{pmatrix}$$

$$\Rightarrow M_n = \vec{P}_n \cdot \vec{S}$$

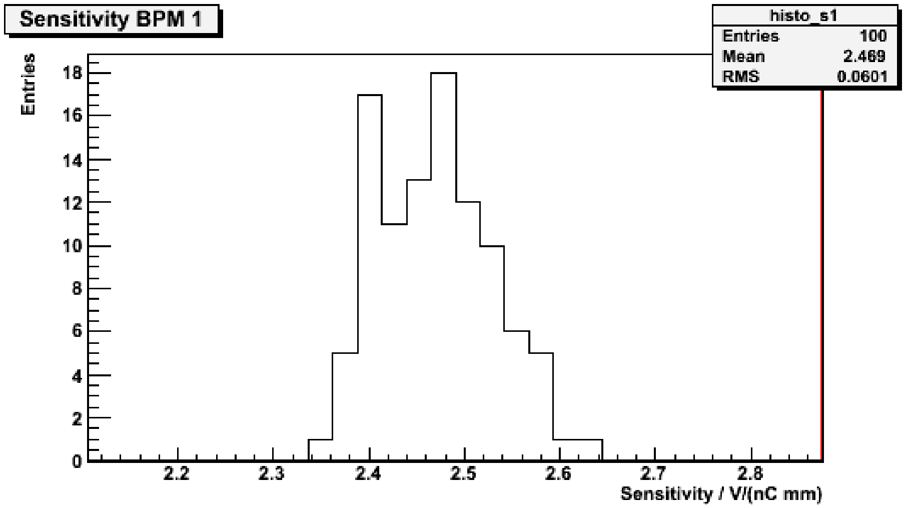
Taking several measurement at different mover position m_i:

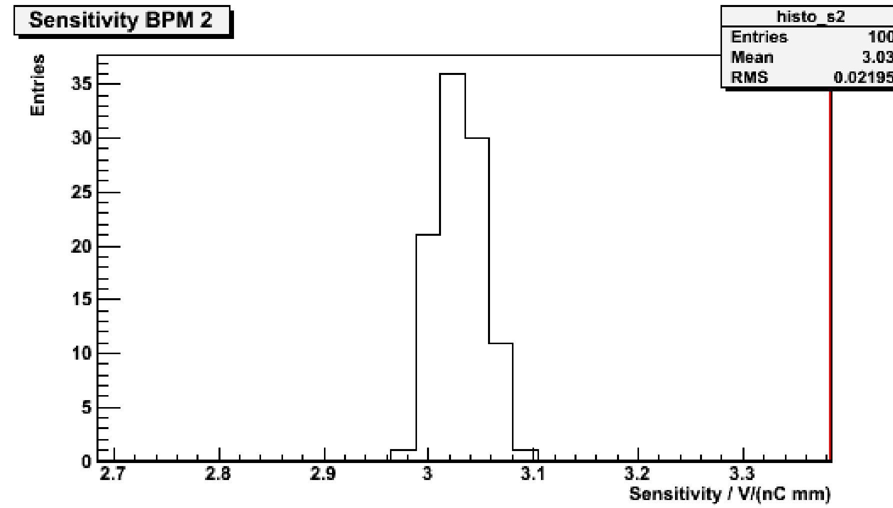
M_n becomes a vector, P_n becomes a matrix P and the solution is:

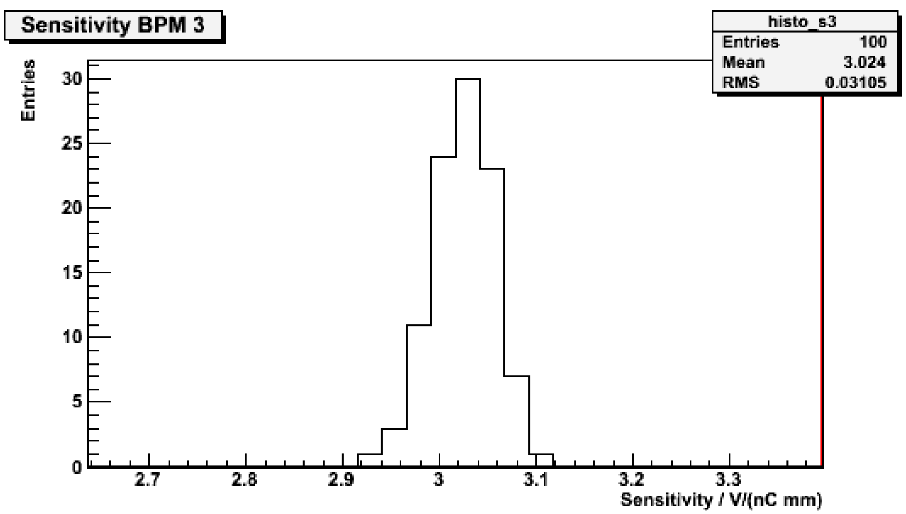
$$P^{-1}\vec{M} = \vec{S}$$

A beam jitter independent position calibration!

Calibration result of Undulator BPM horizontally







Three undulator BPMs in horizontal direction taken and one reference resonator (1.1); all four channels of oscilloscope occupied.

Calibration result of Undulator BPM

	Sensitivity Measurement / V/(nC mm)	Expected Sensitivity with laboratory measurement / V/(nC mm)
1.1 horizontal	$2.47 \pm 0.06_{stat} \pm 0.37_{syst}$	2.83
1.1 vertical	$2.90 \pm 0.03_{stat} \pm 0.44_{syst}$	
1.2 horizontal	$3.03 \pm 0.02_{stat} \pm 0.45_{syst}$	2.90
1.2 vertical	$3.08 \pm 0.02_{stat} \pm 0.46_{syst}$	

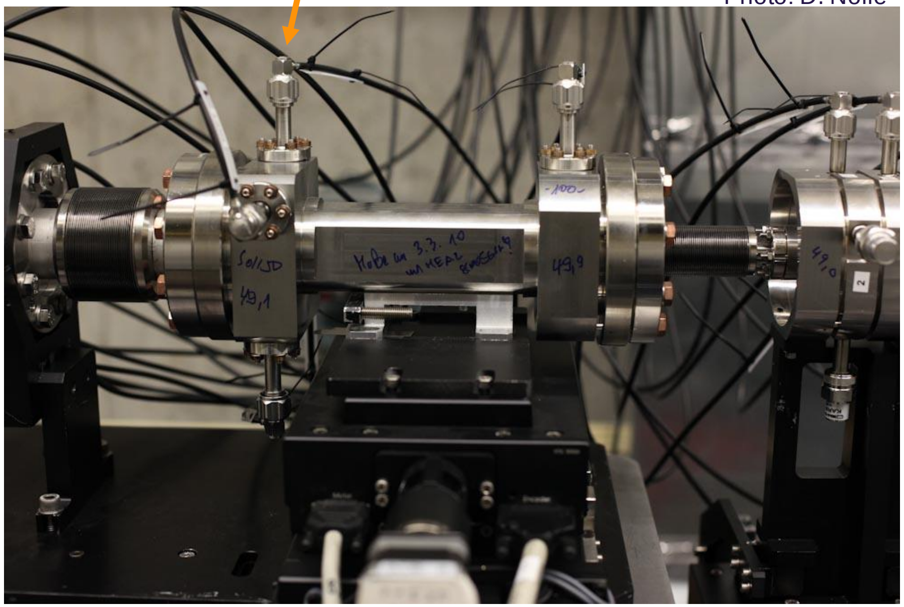
- Sensitivity agree with expectation: here symmetry exist, therefore simulation can predict performance

European XFEL

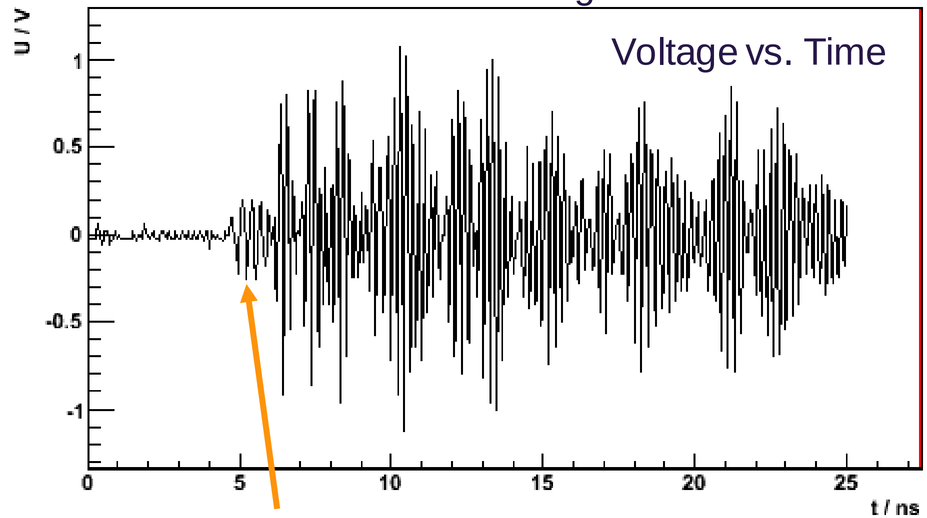
Beamline Cavity BPM Dipole Signal

Connectors for dipole resonator

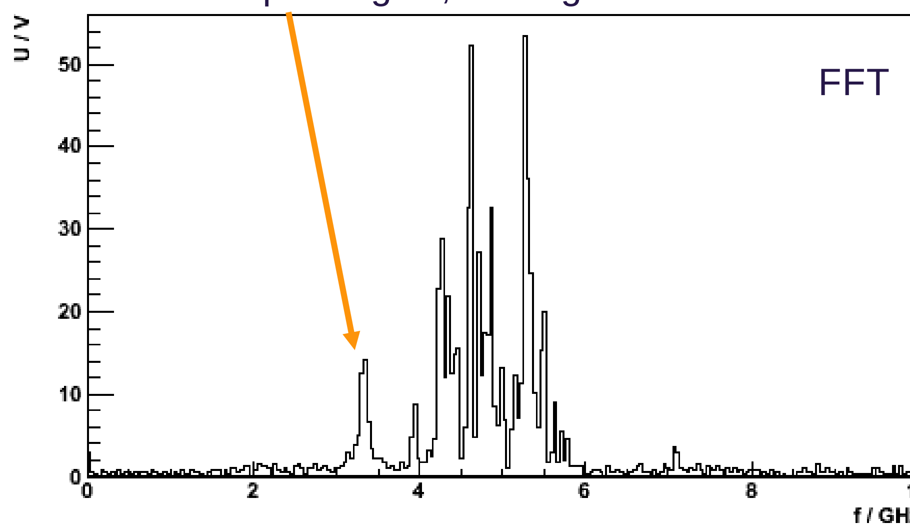
Photo: D. Nölle



About 0.2 mm offset at charge 0.8 nC



Dipole signal, and higher order modes



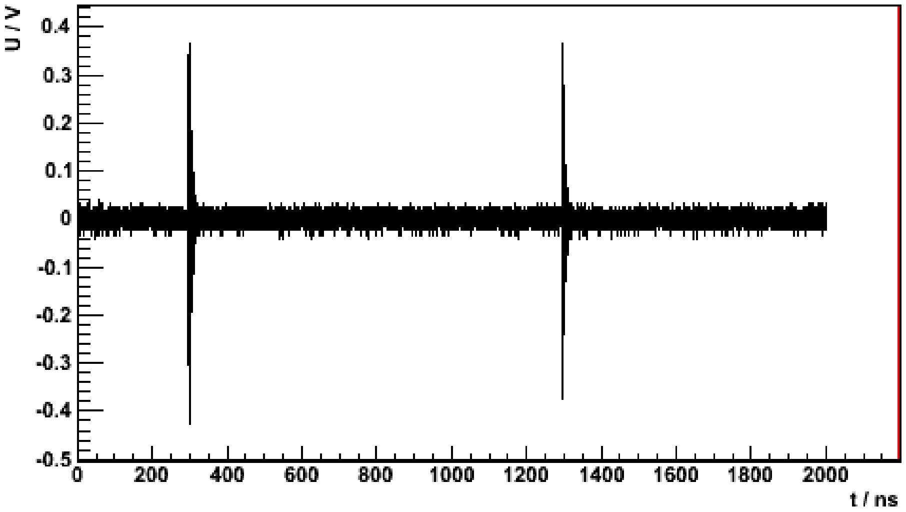
Use low-pass filter with about 5 GHz threshold, but still higher order modes visible.

Should not be a problem for electronics because band-pass filters used.

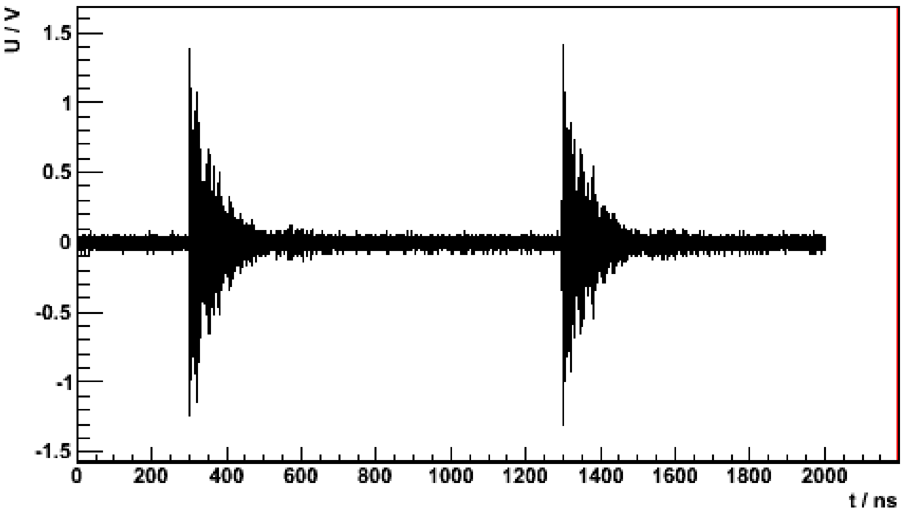
Therefore the following analysis in frequency domain

Dipole signal with 2 bunches

Undulator Cavity BPM Signal



Beamline Cavity BPM Signal



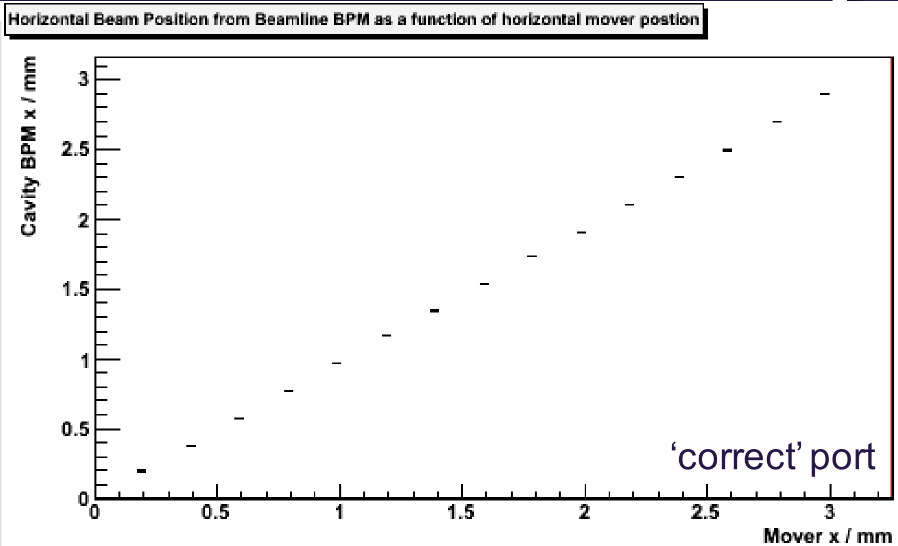
- Faster decay for undulator cavity BPM signal
- Decay time of Beamline dipole signal is similar, only higher order modes decay slower; here without band-pass filter
- But: bunch spacing of 222 ns will be resolved because decay of higher order modes is fast enough

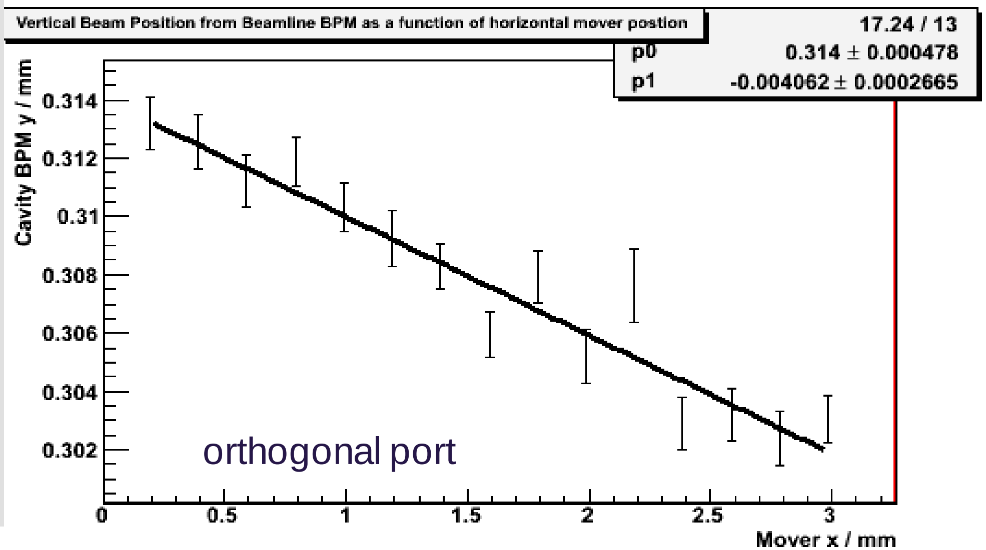
Beamline cavity BPM calibration result

- By using Undulator cavity BPMs 1.1 and 1.3 together with Beamline BPM 2.1 the same method of dipole signal calibration can be applied
- Recalculating sensitivity in time domain results in $1.74 \pm 0.01_{stat} \pm 0.26_{syst}$ for horizontal and $1.81 \pm 0.02_{stat} \pm 0.27_{syst}$ V/(nC mm) for vertical direction
- Expected from laboratory measurement (resonance frequency and quality factor) in combination of simulation (R/Q) results in 2.03 V/(nC mm)
- Explanation: Measurement in time domain is dominated by higher order modes therefore ADC of oscilloscope can not resolve the small dipole signal very well => smaller amplitude in frequency domain

Orthogonal Coupling of Beamline BPM

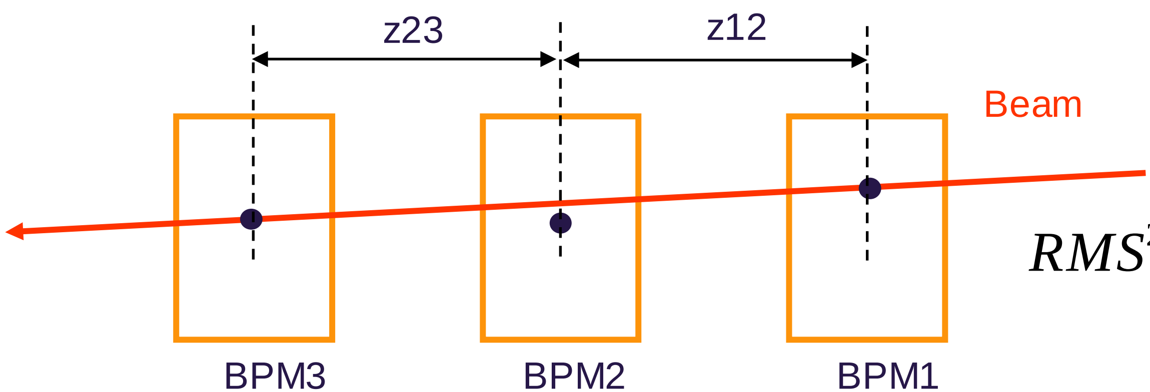
- Calibration used to calculate position; here with Beamline cavity BPM
- Orthogonal coupling of Undulator cavity BPM measured 2009 below -43 dB
- Prove of mechanical accuracy
- Same procedure used here for Beamline cavity BPM by moving in one direction and monitor both coordinates, test of fabrication precision
- Coupling results in (-47.5 ± 0.6) dB; requirement: <-40 dB





Resolution Measurements Principle

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

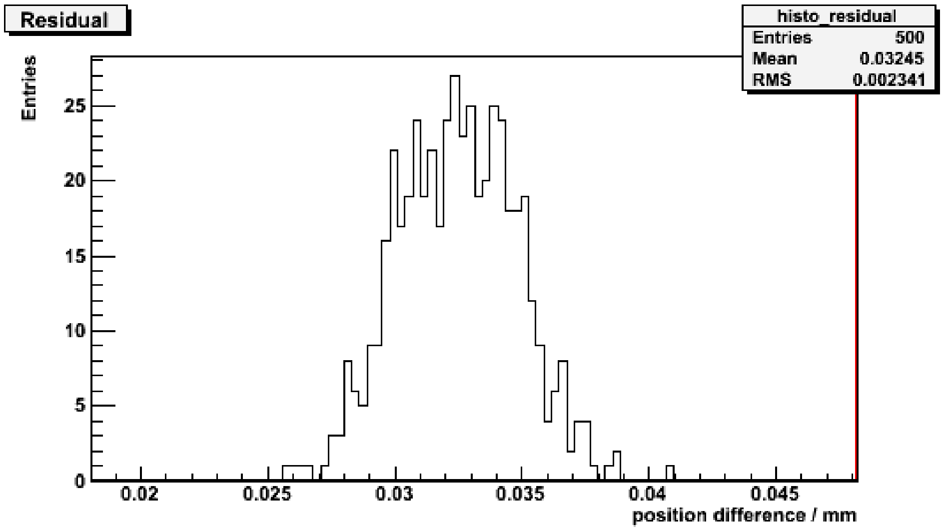


$$RMS^2 = R_2^2 + \left(\frac{z_{12}}{z_{13}} R_1\right)^2 + \left(\frac{z_{23}}{z_{13}} R_3\right)^2$$

- For undulator BPMs $R_2 = R_1 = R_3$
- For Beamline BPM: 1.1 and 1.3 are used with known $R_{undulator}$

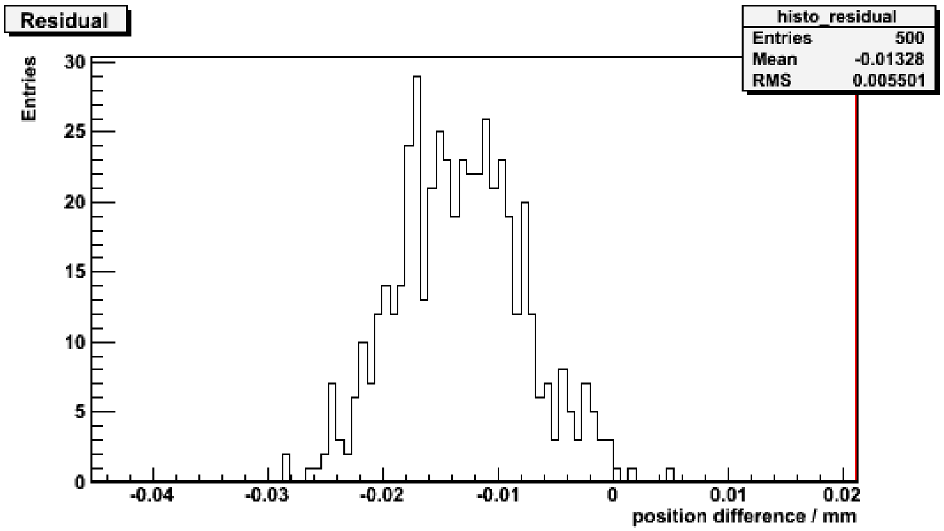
Resolution Results with oscilloscope

Charge = 0.83 nC



Undulator BPMs

Resolution = 1.9 µm



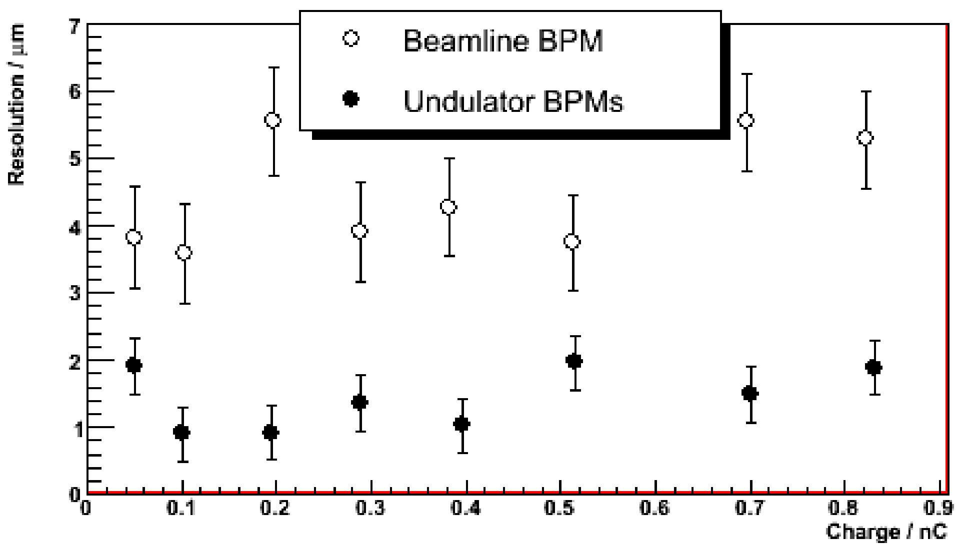
Beamline BPM

Resolution = 5.3 µm

- Resolution of Undulator BPMs better because higher order modes of beamline BPM suppress dipole signal

Resolution vs. Charge with oscilloscope

- No trend shown with charge because oscilloscope amplitude range manually adapted
- Below 40 pC not measured because of limited amplitude range of oscilloscope
- Beamline BPM resolution always higher compared to undulator BPMs because of higher order modes
- Resolution of undulator BPMs between 0.8 and 2 µm (Requirement: below 1 µm for charge range 0.1 to 1 nC)



In the analysis not considered:

- Beam angle
- Beam tilt

Which adds dipole signal at the same frequency but with phase offset of 90˚

Electronics from PSI will improve!

Status Cavity BPMs

- Production of feedthrough for mass production ongoing

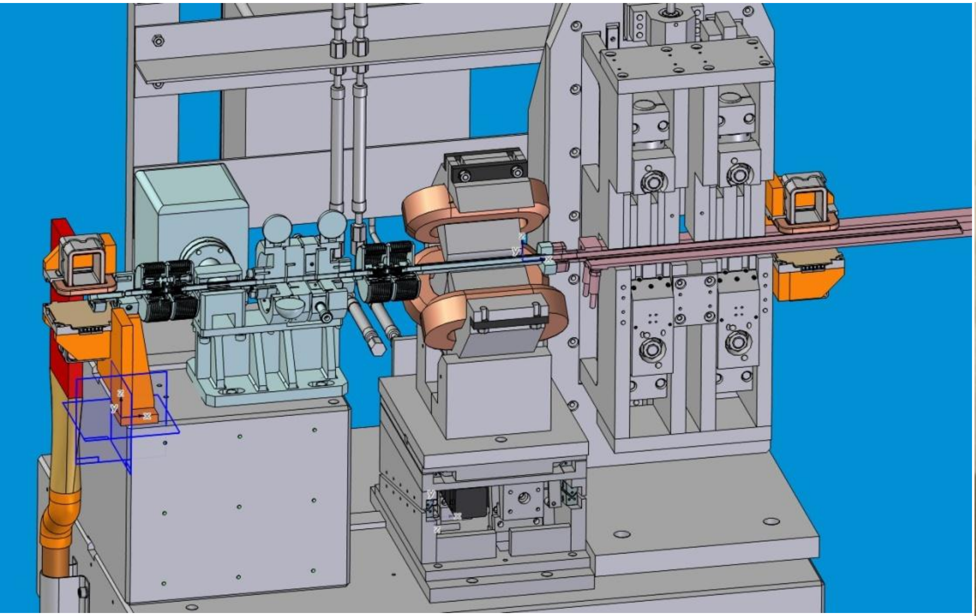
Photo: D. Nölle

- Optimized brazing position of reference resonator (nearer to the resonator for better conductivity)
- Found systematic shift of reference resonator resonance frequency between measurement and simulation (reason non-symmetry of resonator)
- Call for tender of undulator cavity BPMs ongoing

SUCA prototype

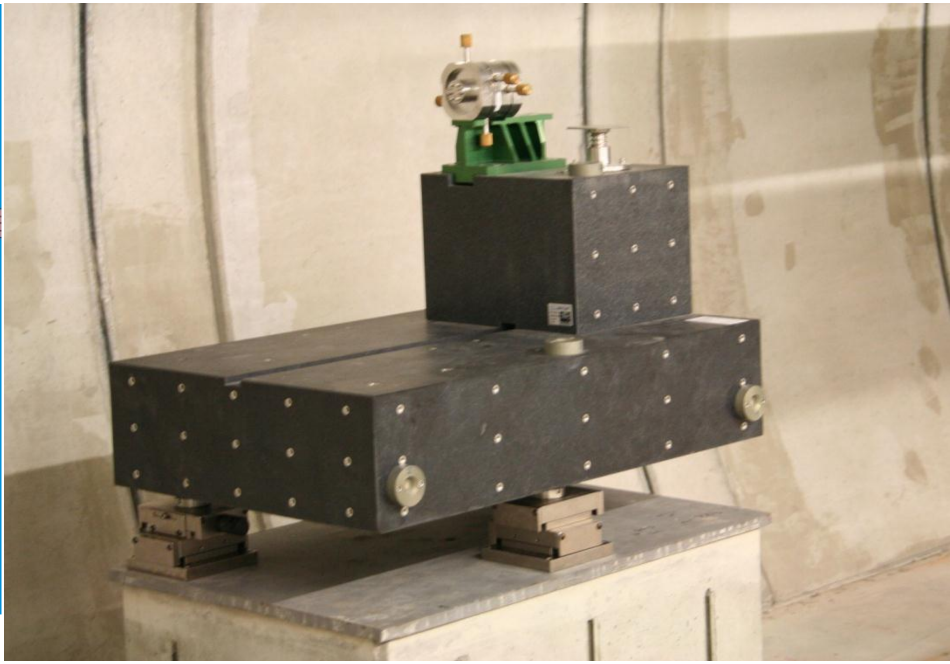
SUCA: Standard Undulator Cell Assembly

Model with air coil, bellow, pump, cavity BPM, bellow, quadrupole, phase shifter and air coil



Courtesy: T. Wohlenberg

Photo shows the undulator cavity BPM, mounted on the SUCA prototype



In MockUp Tunnel, 24.08.2010

Single reference resonator for dark current and beam charge measurements

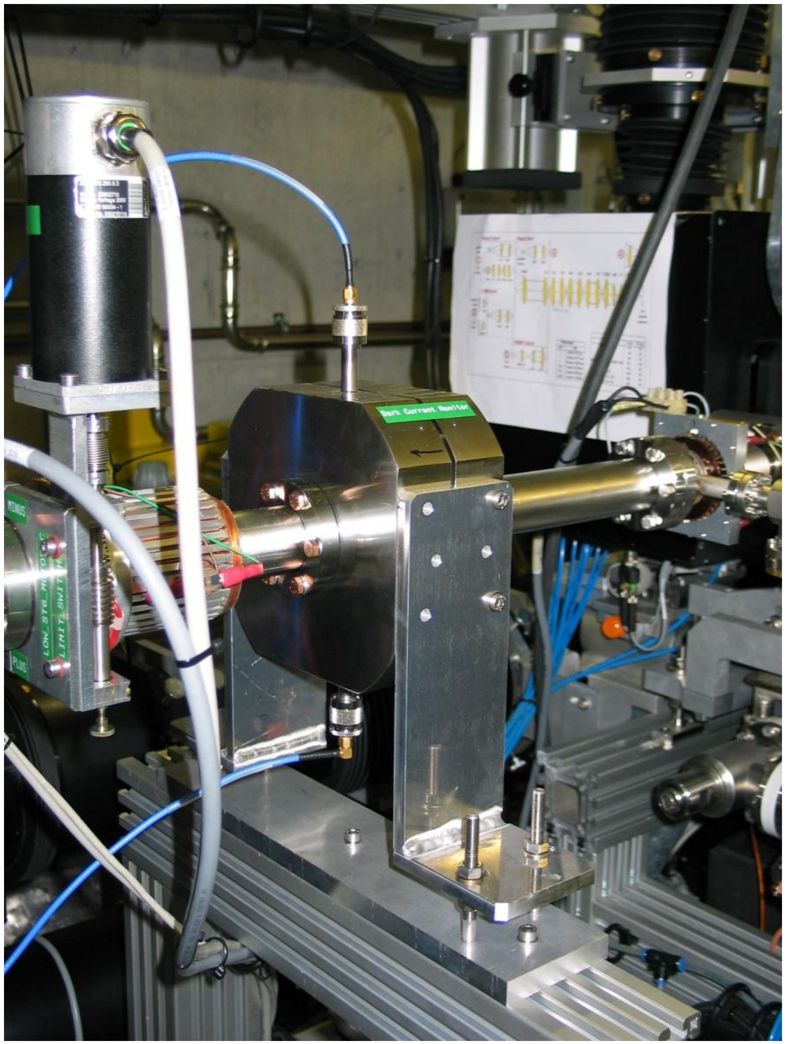
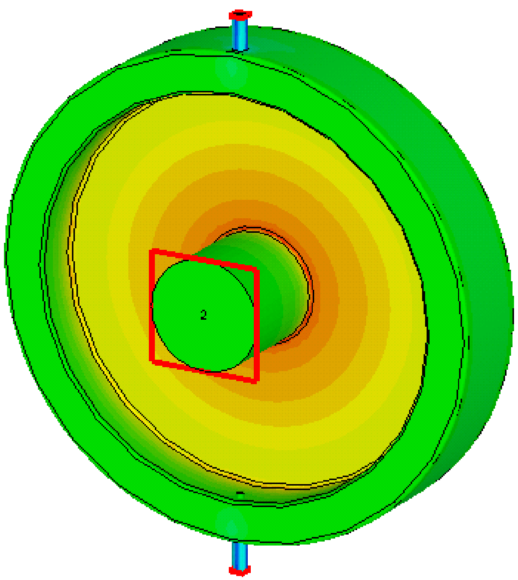


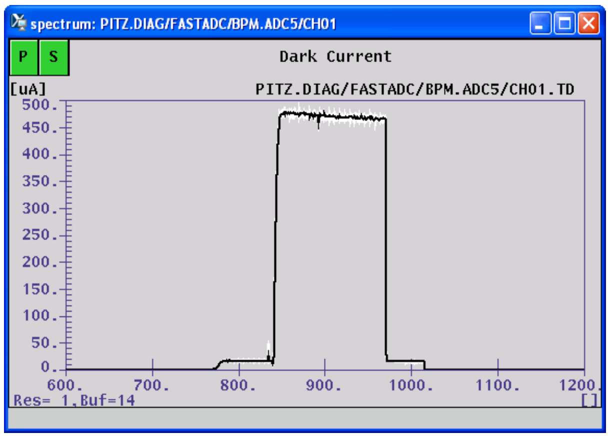
Photo: J. Lund-Nielsen

- Monopole mode with 1.3 GHz and Q_L=205 design; produced 5 with 1.2993 GHz and 193 without tuners.
- Dark current will superimpose induced field in cavity to a measurable level when acceleration with 1.3 GHz.
- In addition charge measurement.
- Developed electronics with logarithmic detector for high dynamic range.

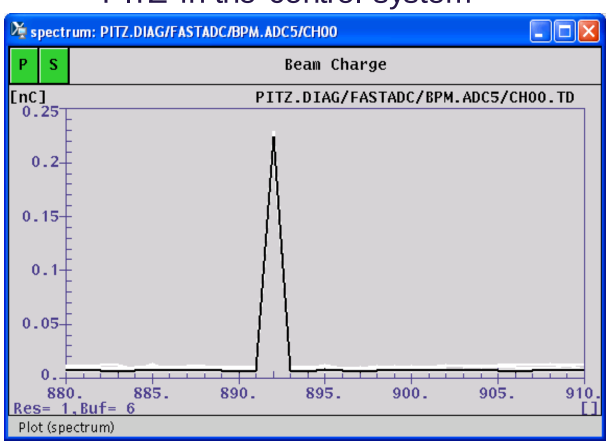


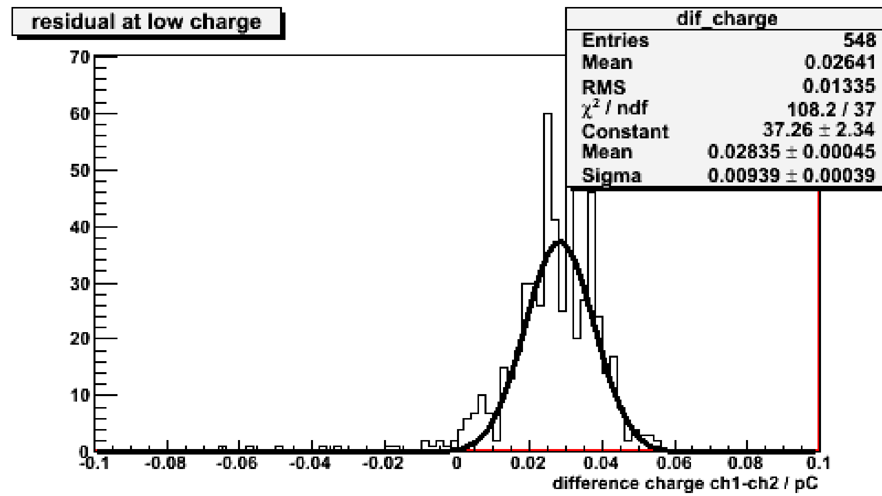
Single reference resonator for dark current and beam charge measurements

Dark current at the Photo Injector Test facility at Zeuthen (PITZ) with results visible from the gun (low level) and booster (high level) in the control system



Charge measurement at PITZ in the control system





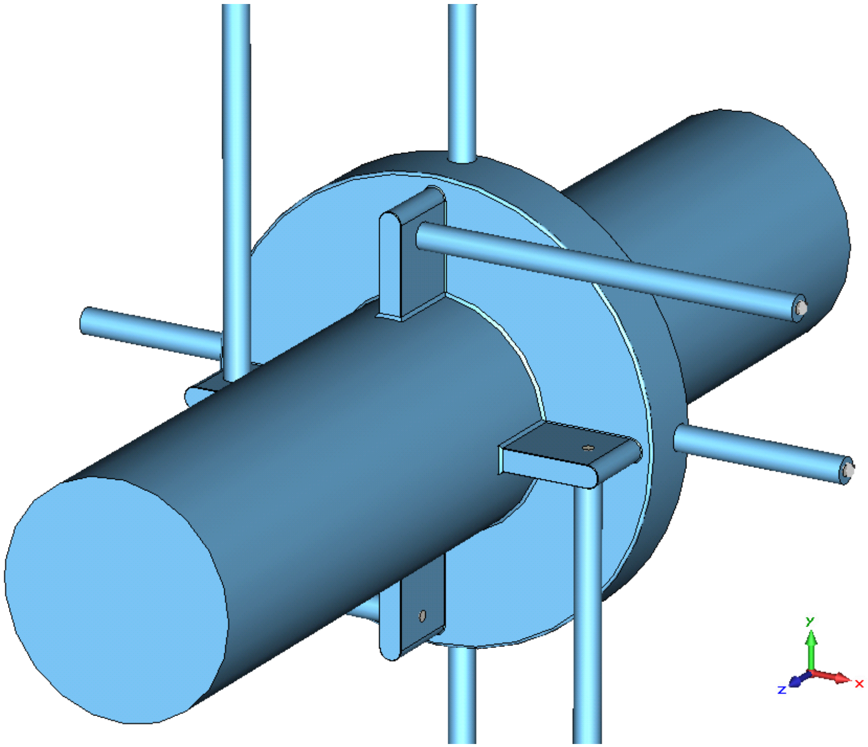
- Measurement at Relativistic Electron Gun for Atomic Exploration (REGAE).
- Here goal measure only charge because accelerator with 3 GHz.
- Above the calibrated difference of both electronics branches for charge of about 200 fC.
- Taking into account oscilloscope ADC influence the resolution of both electronics is 4 fC

Redesign Beamline Cavity BPM: shorter

- Goal: shorter cavity BPM with large tube to upgrade diagnostics, replace Button BPMs (length 150 mm)
- Reduction of length of 105 mm necessary

Solutions:

- Survive with resonator crosstalk: -48 dB, corresponds offset of 70 µm
- Reduce resonator coupling by changing coupling of resonator to tube (without slot tube connection, smaller resonator thickness …)
- Only one resonator with monopole mode antennae at lower frequency
  - Process monopole signal at different frequency, problem running phase difference
  - Process monopole signal at dipole frequency with reduced sensitivity: -27.6 dB



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Summary

- Design based on T. Shintake
- Two kinds of cavity BPMs: undulator and beamline, similar properties for same electronics
- BPM Test Stand at FLASH
- measurements with oscilloscope
- Resolution of Undulator BPM between 0.8 and 2 µm for required charge range
- Resolution of Beamline BPM between 3.7 and 5.4 µm for required charge range (requirement 10 µm)
- Will be improved with PSI electronics!
- Prototype on SUCA test stand
- Single resonator used for dark current and charge measurements
- Work on redesign for shorter beamline cavity BPM

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