Pile-Up Effect of cold Button BPMs in the European XFEL Accelerator

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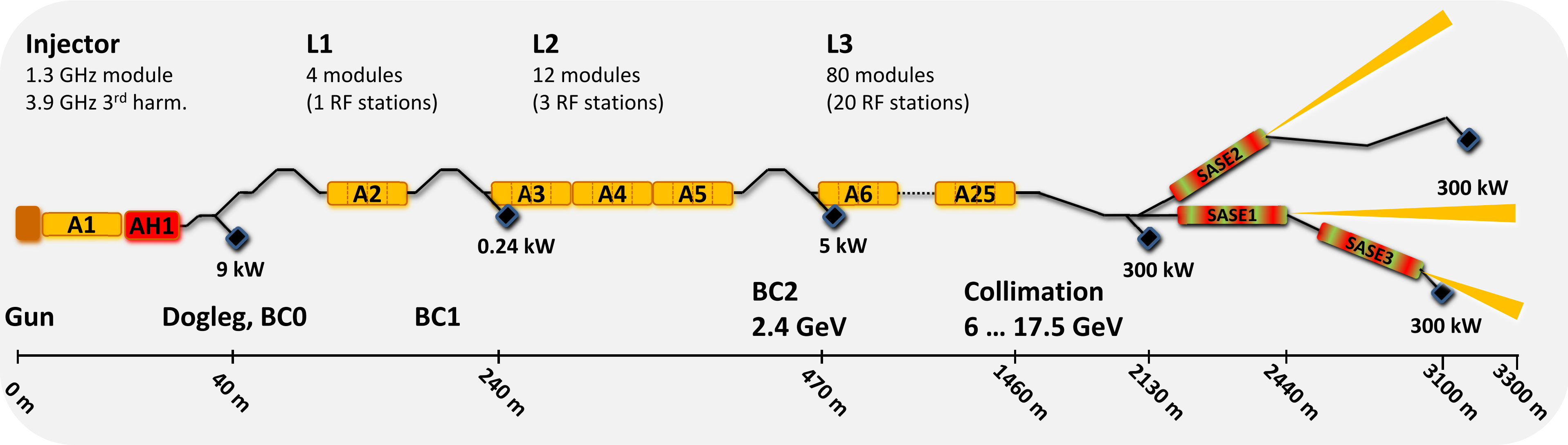
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

- The European XFEL
- Diagnostics in the Cryogenic Accelerator
- Unexpected effect with few Button BPMs visible
- Monitor or Electronics?
- Dependencies of Signal on Charge and Position
- Monitor investigation without beam
- Origin of Pile-Up: button with beam
- Hypothesis
- Summary and Outlook
- Alternatives

The European XFEL

Schematic Accelerator Overview

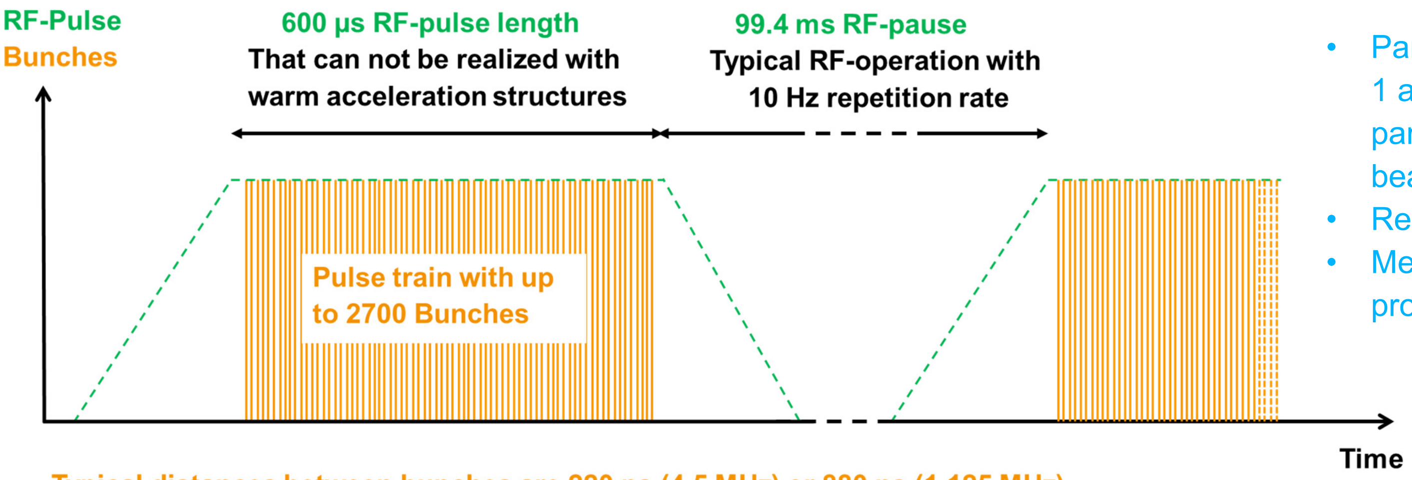


- 98 superconducting accelerator modules are used to accelerate the beam in the European XFEL up to 17.5 GeV.
- Length: 3.5 km, L3 about 1 km,
- SASE 1 and 2 for hard and SASE 3 for soft X-rays

Courtesy Matthias Scholz, DESY

The European XFEL

Long Pulse Trains



Typical distances between bunches are 220 ns (4.5 MHz) or 880 ns (1.125 MHz).

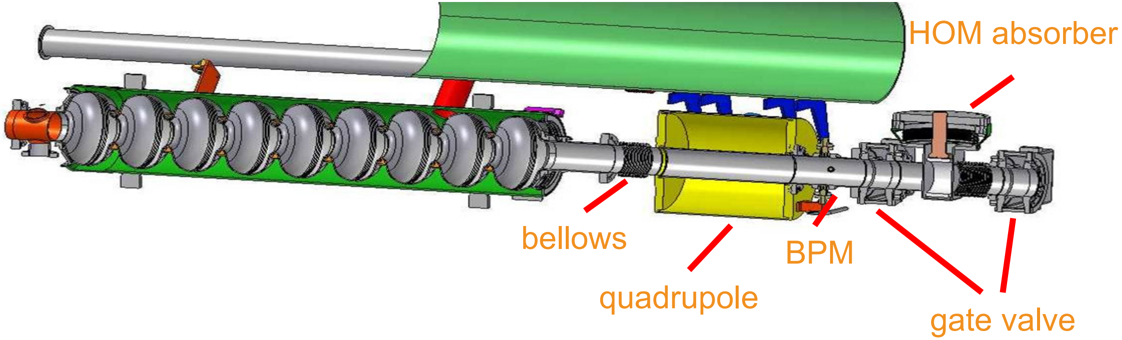
- Parts of train distributed to SASE 1 and 3, other part to SASE 2: parallel operation of all undulator beamlines
- Realized with flat-top-kickers
- Measurement of single bunch properties necessary

Courtesy Matthias Scholz, DESY

Diagnostics in the Cryogenic Accelerator

BPMs in the accelerator

- 96 (+2 injector) superconducting modules are installed
- RF components are installed in racks below the accelerator, no access during operation possible
- Each module contains one BPM: 24 reentrant cavity and 74 button BPMs



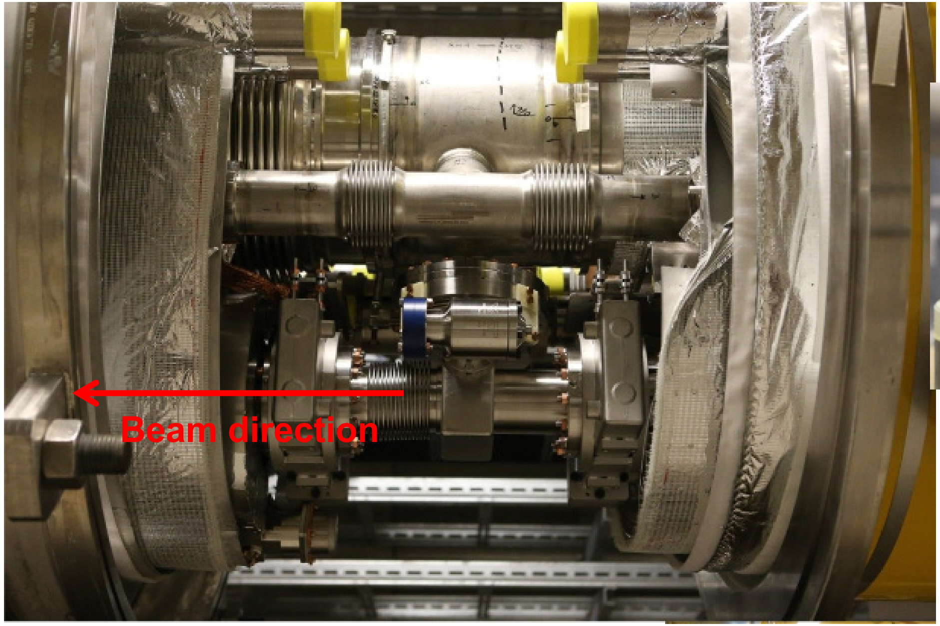
After each last accelerator cavity in one module follows:

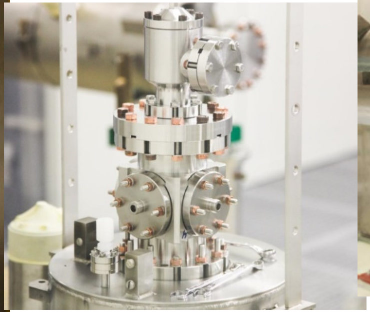
- bellow, cold quadrupole, BPM, valve, higher order absorber, valve with each 78 mm inner diameter tube

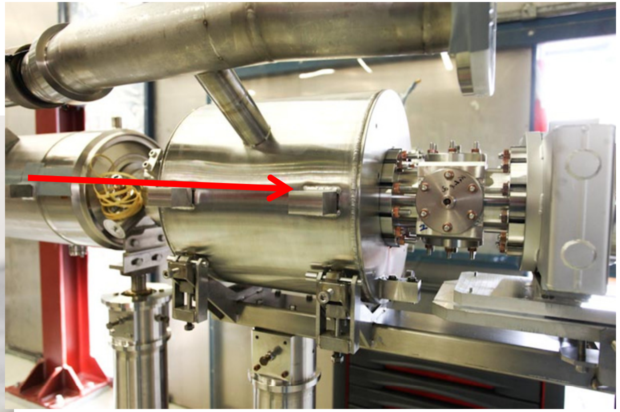
Diagnostics in the Cryogenic Accelerator

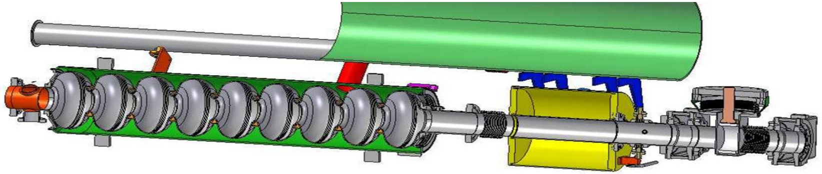
Button BPMs in the accelerator

- Button BPM with 16 mm diameter and 19 mm housing in stainless steel
- Electronics RFFE 3-dB bandwidth between 1.53 and 2.28 GHz, installed below the modules in the tunnel









Unexpected effect with few Button BPMs visible

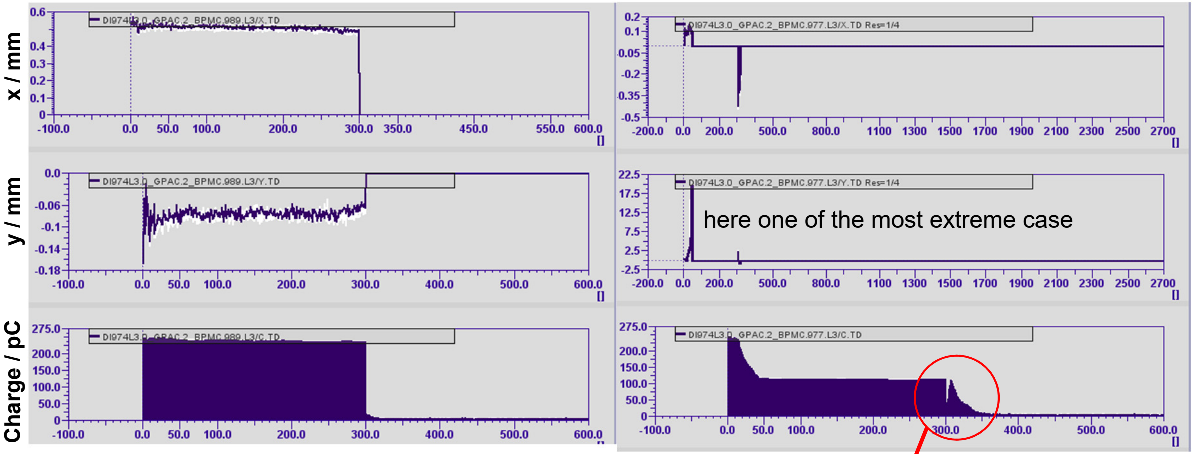
Sum Signal (= charge) shows strange distribution

- Most of cold button BPMs work like expected
- 17 out of 74 (23%) showed a strange charge distribution along the bunch train:
  - Charge drops after few bunches to about the half of charge
  - When bunches are disappeared it still showed calculated charges
  - Beam positions are wrong calculated when charge slope is large

Operation with 4.5 MHz repetition rate and 300 bunches

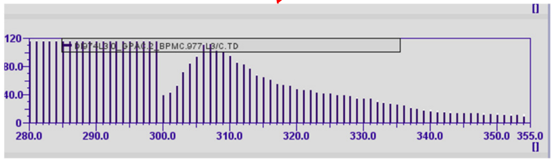
BPM correct

BPM with wrong distribution



bunch in train

bunch in train



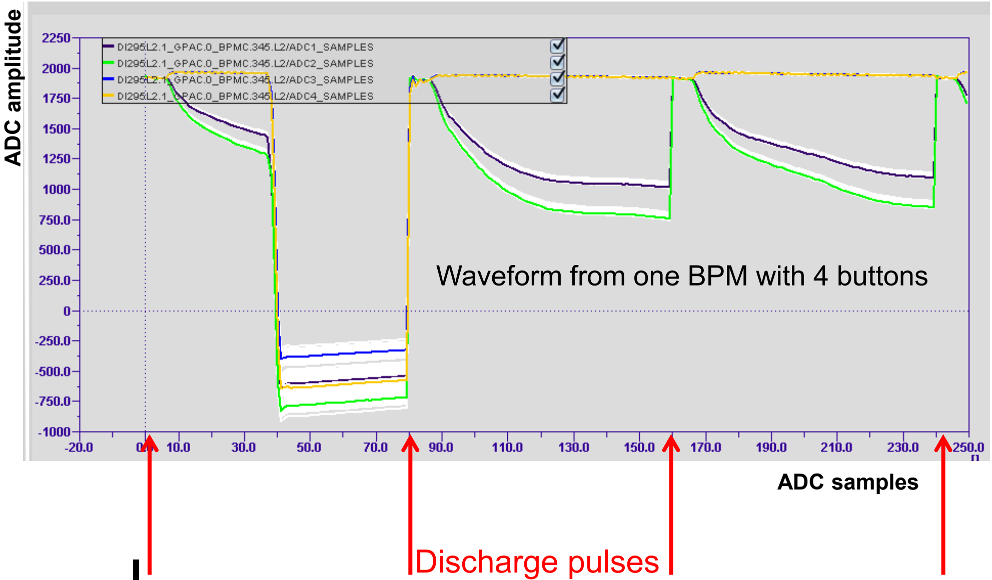
Remarkable button BPM signals

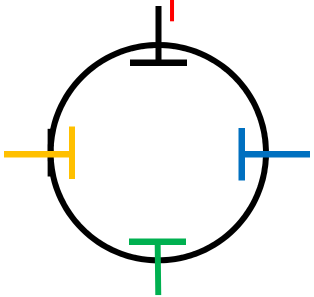
Waveform from one affected BPM

- Expected „rectangular“ shape for each filled bunch bucket
- Baseline is at about 1950 ADC amplitude
- Change of the expected shape in baseline starting, it becomes stronger with number of bunches until reaches an equilibrium
- This influences the signal amplitudes and the calculation of the position and charge values
- E.g. the difference between signal and baseline is reduced therefore the sum (charge) signal value is lower

- Outline of following investigations: Electronics, depends on beam property, monitor resonances, spectrum with beam, compare with expectation.

1.1 MHz repetition rate and 100th beam bucket





This example only vertical buttons are affected (mostly the case), few BPMs show horizontally effect and 2 both directions

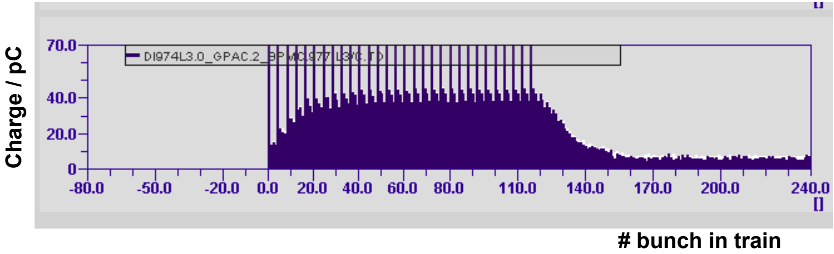
Monitor or Electronics?

Just swap the cables in front of two RFFEs with different behaviors

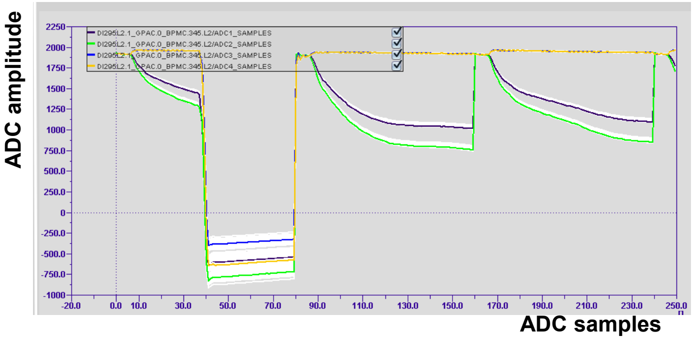
Waited until an access was granted, swapped the cables and found:

- The signal moved with the monitor to the other electronics
- The behavior is not caused from the electronics
- -> the monitor delivers a superimposing signal even with discharge = Pile-Up

Operation with 1.1 MHz repetition rate and 30 bunches each with 250 pC, after swapping of cables



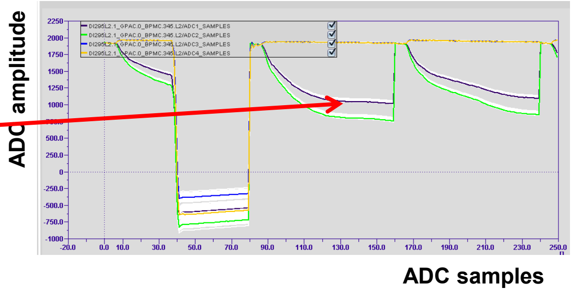
With 1.1 MHz repetition rate each 4th bunch bucket is filled, here the calculated charge of the empty buckets from the Pile-Up is visible and causes non-negligible charge values
This is caused by the still existing signal in the empty buckets.



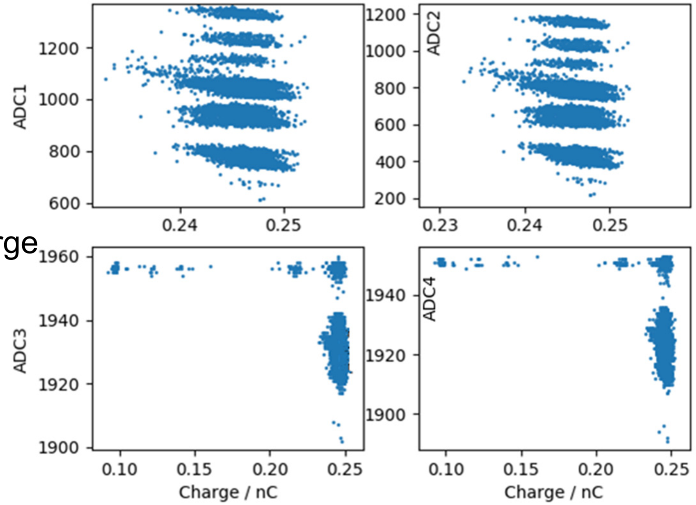
Dependencies of Signal on Charge and Position

Measurement parasitically during beam operation

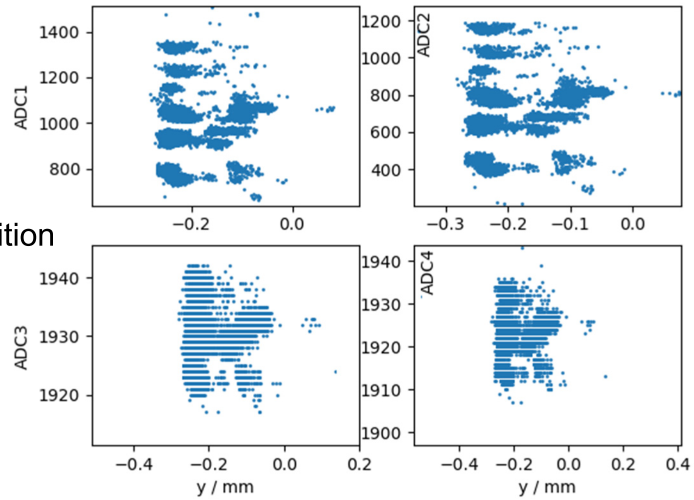
- Measurement of the baseline ADC amplitude of an empty bucket at 1.1 MHz bunch rep. rate.
- When amplitude lower than 1950 Pile-Up is visible



Charge



Position



Signal is correlated with the beam charge and position of first bunch for ADC1 and 2; are the vertical buttons

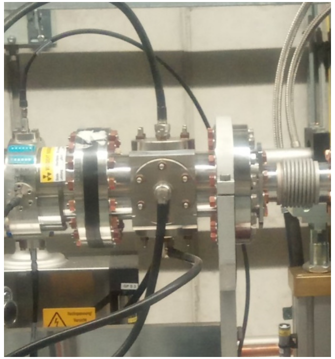
No correlation with position visible; steps are caused by different attenuators, similar for horizontal plane

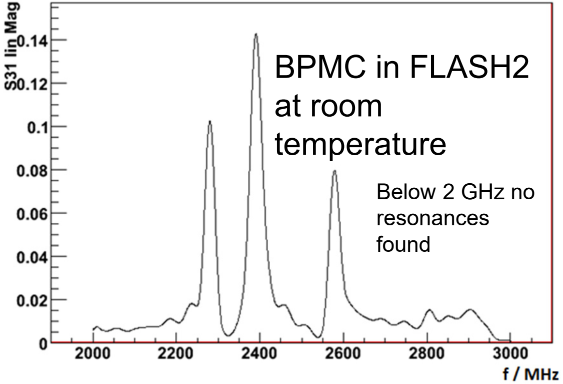
Monitor investigation without beam

Measurements with Network Analyzer at E-XFEL and FLASH2

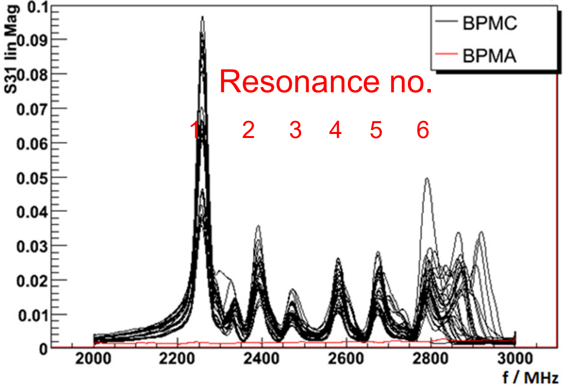
Check resonances of BPM and compare with warm prototype in FLASH

One prototype of BPMC (= cold button BPM) installed in FLASH2





BPMC in XFEL at cryogenic temperature, BPMA other button type



		1	2	3	4	5	6
XFEL	f / MHz	2257.5 ± 0.8	2392.1 ± 2.2	2471.2 ± 3.6	2582.5 ± 3.4	2674.6 ± 2.1	2793.1 ± 6.2
XFEL	Q	97.7 ± 4.6	76.4 ± 9.5	57 ± 27	106 ± 20	79 ± 13	81 ± 18
FLASH2	f / MHz	2281.0	2391.1	-	2578.8	-	-
FLASH2	Q	109.6	91.8	-	99.7	-	-

- Measurement of several BPMs during maintenance
- Additional resonance at 2.47 GHz visible
- Quality factors too low to generate a significant signal after 222 ns
- Effect not caused from the monitor itself

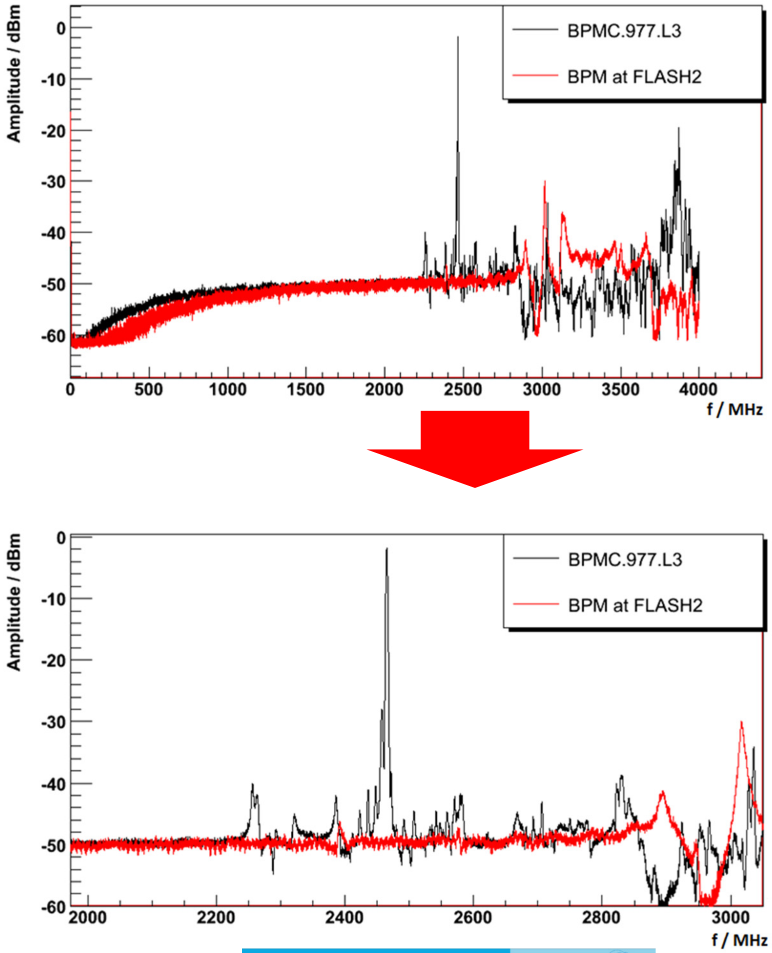
3 resonance frequencies and quality factors from FLASH2 BPM nearby to XFEL results

First resonance Δ frequency of 23.5 MHz but warm-cool temperature diff.

Origin of Pile-Up: button with beam

Signals from the Monitor with accelerator cavity

- Frequency range up to 4 GHz, Spectrum analyzer installed in a rack in the tunnel with remote access (switching from one channel to another only during the seldom accesses possible)
- Cut-Off frequency is 3 GHz
- No resonance at the acceleration frequency 1.3 GHz measured
- Resonances visible between 2.2 and 3 GHz
- Prototype at FLASH does not show these resonances



Measurements of Spectrum

Signals from the Monitor during user run

- Measurement of two different BPMs with a distance of 24 m show similar resonances

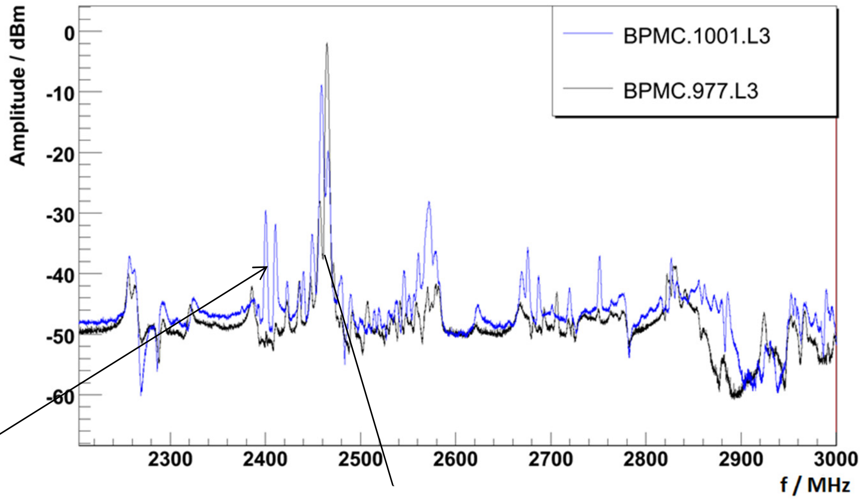
- Dominant resonances are above -33 dBm and below 2.5 GHz:

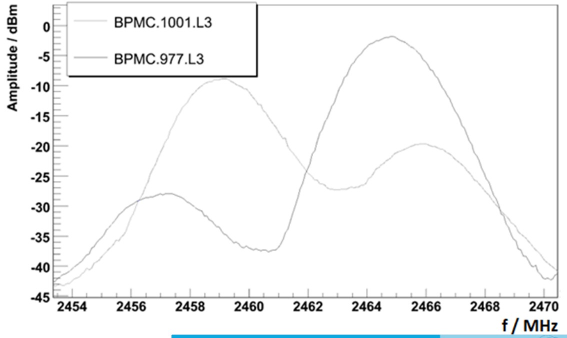
  - 2464.7 MHz with Q = 1232, τ = 159 ns,
  - 2457.1 MHz with Q = 945, τ = 122 ns

  BPMC.977

  - 2400.3 MHz and 2410.4 MHz with τ = 159 ns each
  - 2459 MHz with Q = 1242, τ = 161 ns
  - 2465.7 MHz with Q = 1006, τ = 130 ns

  BPMC.1001





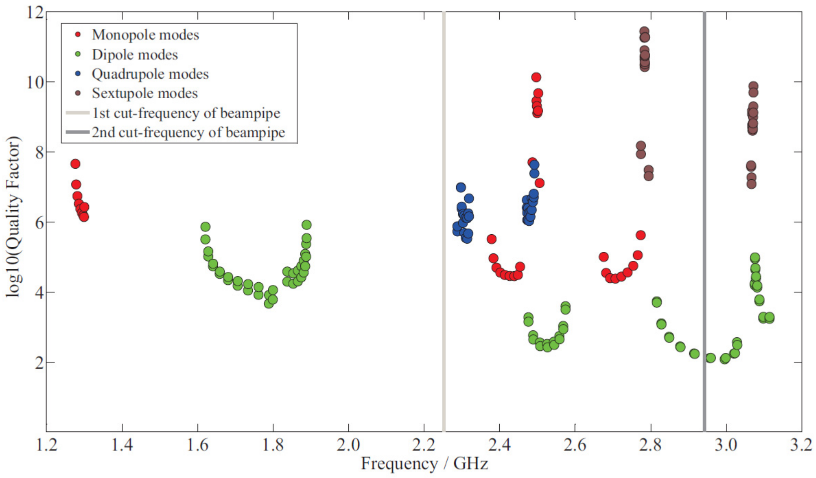
- These resonances with large amplitudes decays slowly such that the next bunch bucket with 222 ns distance (4.5 MHz) will be influenced

Hypothesis: resonances from the cavity

Higher Order Mode simulations of the Accelerator Cavity

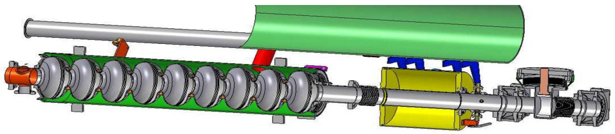
- Resonances between 2400 and 2470 MHz with high amplitude and quality factor causes the Pile-Up effect seen in the cold BPM
- On the right side the simulated higher order modes of the accelerator cavity
- Above 2.4 GHz monopole, dipole and quadrupole modes are expected

Ref: C. Liu, W. Ackermann, W. F. O. Müller, and T. Weiland, “Numerical Calculation of Electromagnetic Fields in Acceleration Cavities Under Precise Consideration of Coupler Structures”, in Proc. 4th Int. Particle Accelerator Conf. (IPAC'13), Shanghai, China, May 2013, paper MOPWO007, pp. 897-899



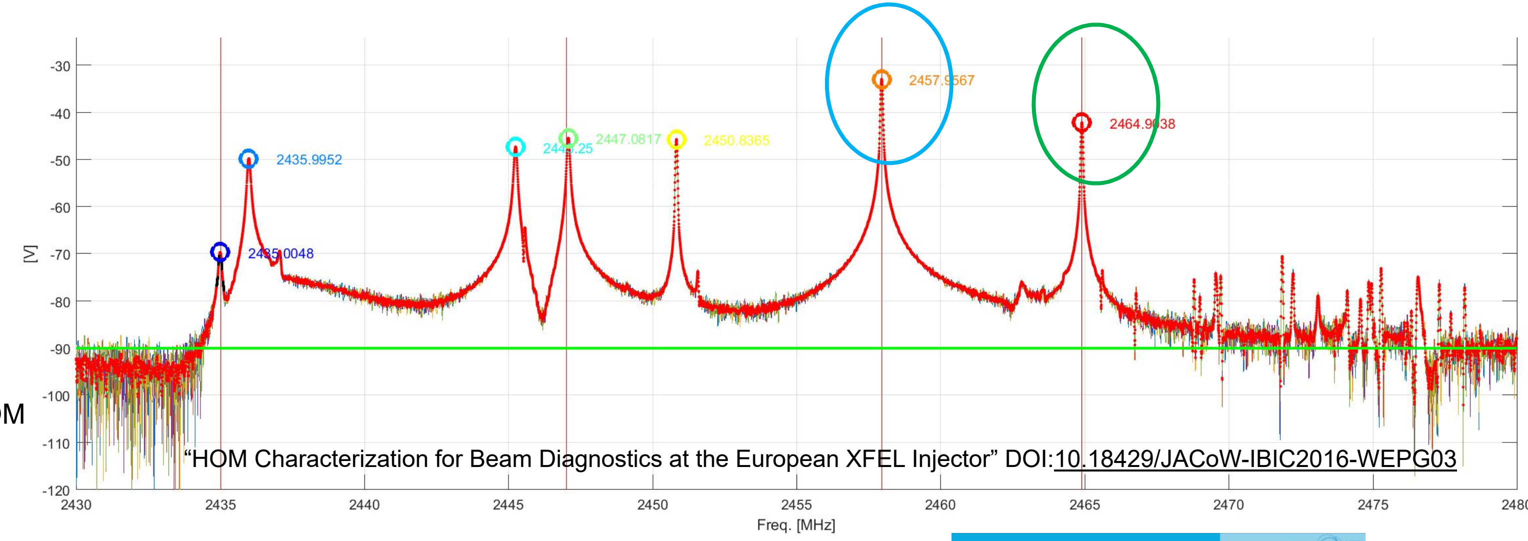
Hypothesis test

Spectrum with HOM coupler



- Similar resonances measured with the HOM coupler after the BPM, see diagram
- Compare with resonances: **2457.1 MHz, 2459 MHz**, **2464.7 MHz and 2465.7 MHz** from cold button BPM

- But each cavity shows a variation of resonance frequency in MHz range
- Amplitude HOM from each cavity is different too
- This explains that not all BPMs are affected by the HOMs



“HOM Characterization for Beam Diagnostics at the European XFEL Injector” DOI:10.18429/JACoW-IBIC2016-WEPG03

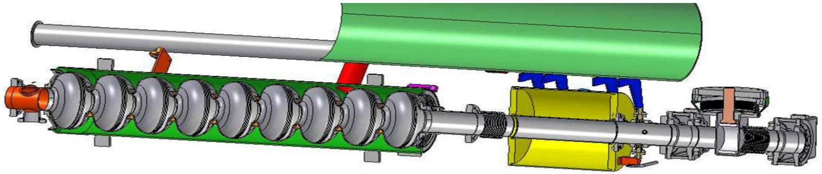
- Vertical lines are the expected monopole HOM

Summary and Outlook

- European XFEL in user operation
- Observed a Pile-Up effect in cold button BPMs installed in the accelerator module
- The Pile-Up effect are not caused by the spectrum of the button itself
- Assumption: it is caused by higher order modes of the accelerator cavity
- These resonances are higher order modes in the accelerator cavity, decreased in the amplitude with the beam pipe of 78 mm diameter (f_{cut} about 3 GHz) and convoluted with the button spectrum
- Mostly a pair of opposite buttons is affected but the signal is caused by a monopole mode; unknown asymmetry

Outlook:

- Reducing influence from HOMs with Low-Pass filter
- Alternative bandwidth of RF electronics



Alternatives

Cut out the HOM frequency range

Tests with Low-Pass Filters

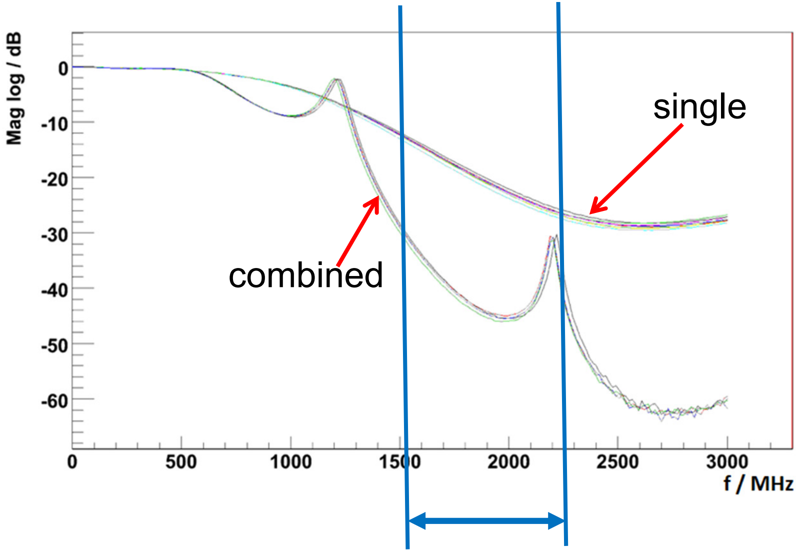
- Test was done before spectrum was measured
- Single low-pass filter reduces amplitude of 2.4 GHz signals by about 25 dB, still Pile-Up was visible, charge calibration increased by factor of 5.9, resolution changed from about 4 µm to 12 µm at 250 pC
- Combined low-pass filter reduces amplitude of 2.4 GHz signals by about 60 dB, Pile-Up not visible, charge calibration increased by a factor of 39, resolution results to be 65 µm at 250 pC (at boundary of requirement)

New read-out electronics

- Alternative electronics installed, first beam tests in preparation

Bessel Low-pass filter (1 GHz) transmission spectrum:

- Single
- Combined two after another



Thank you for your attention

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Back-Up slide: Measurement of Spectrum in Tunnel

Spectrum Analyzer connected with GPIB – network switch for remote control

- During user operation data are taken with constant beam charge
- The spectrum of 0 to 4 GHz is divided in 80 steps: 50 MHz bandwidth
- Each step: „max Hold“ to get maximum value from the beam for each frequency sample, two times with 80 s sweeptime to not loose any frequency sample; one measurement need 3.5 h
- Finalizing: all date are put in one whole frequency diagram.
- Measurements are repeated to verify the results.