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Charge Measurements in SwissFEL and Results of an Absolute Charge Measurement Method

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- Wall Current Monitor: experimental characterization and numerical modelling results
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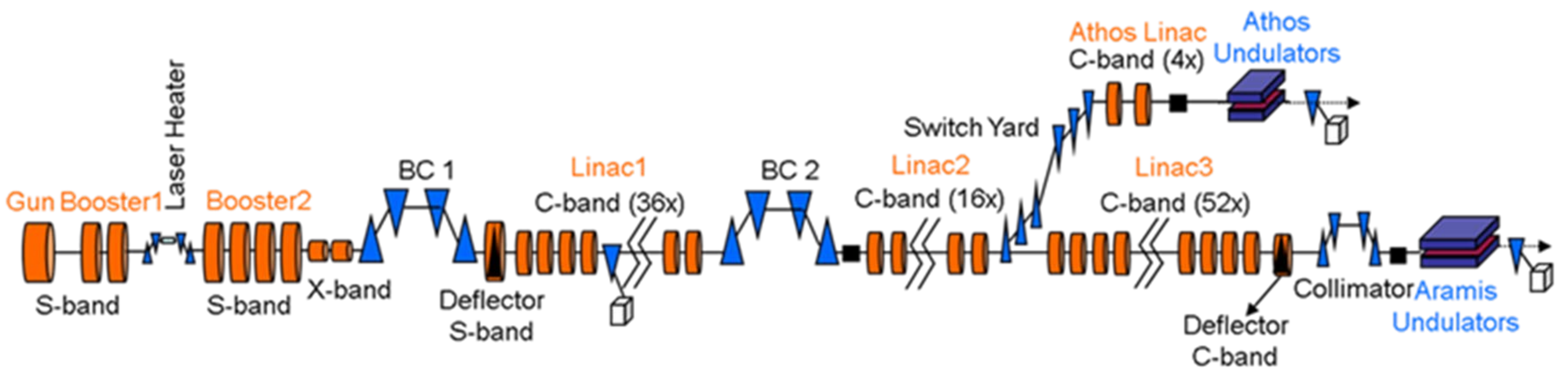
- Charge measurement campaign at SwissFEL
- Procedure for absolute calibration of the SwissFEL charge monitors
- Conclusions

SwissFEL in a sketch



- ➢Beam energy: 6.2 GeV and 3.3 GeV
- ➢Beam charge: 10-200 pC @100Hz, 28 ns 2-bunch time structure
- ➢Emittance: 0.4/0.2 mm mrad
- ➢Bunch length: from a 3 ps up to a few fs
- ➢Photon wavelength: 0.1-0.7 nm and 0.7-7.0 nm

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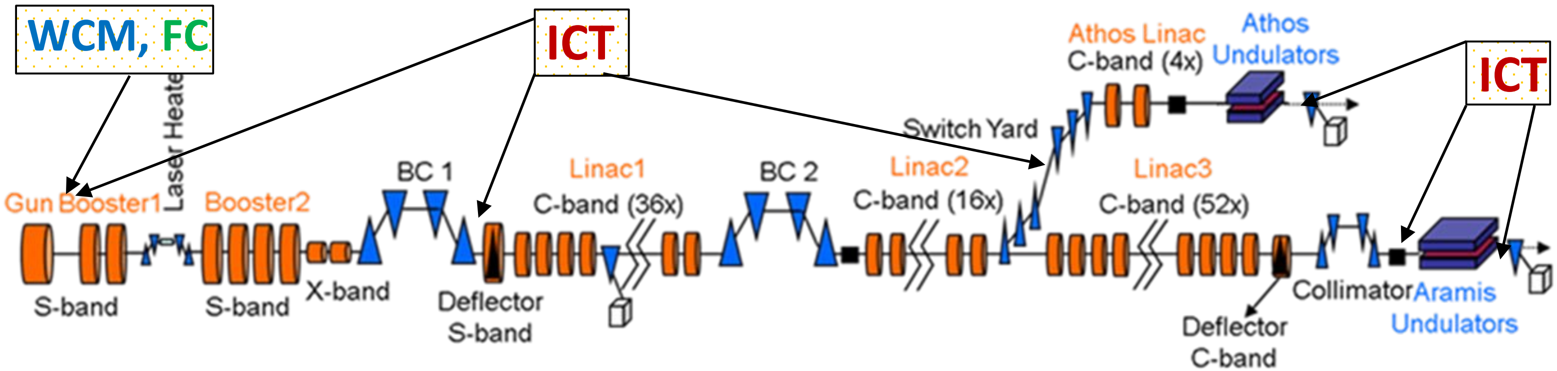
Charge Monitor in SwissFEL

- Turbo ICT (Integrating-Current-Transformer):
  - 4 in Aramis and 2 in Athos
  - 28 ns 2-bunch resolution
- Standard ICT (1 in the gun section):
  - full beam current integral (no 2-bunch discrimination)
- Cavity-BPM (Beam-Position-Monitor):
  - ~200 units distributed all along Aramis and Athos
- Wall-Current-Monitor (WCM, 1 in the gun section):
  - coarse synchronization photocathode laser timing and RF gun phase
  - 2-bunch charge monitoring @100 Hz
- Faraday- Cup (one unit in the Gun section):
  - Dark current

Integrating Current Transformer (ICT)



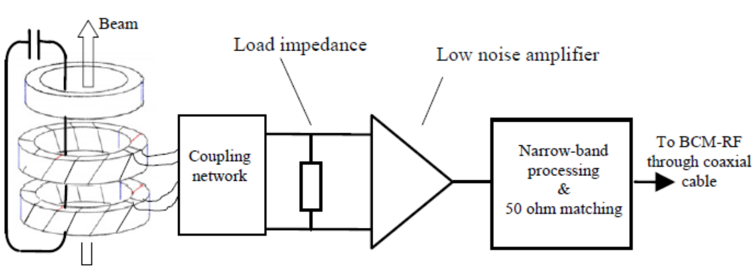
➢ **Standard ICT** (BCM-IHR readout electronics)

- time integration (5µs) of the beam induced current in the transformer
- Broad-band frequency response (kHz➔10 MHz)
- no 2-bunch time structure resolution
- Sensitive to dark current of the gun
- Charge resolution ~ pC

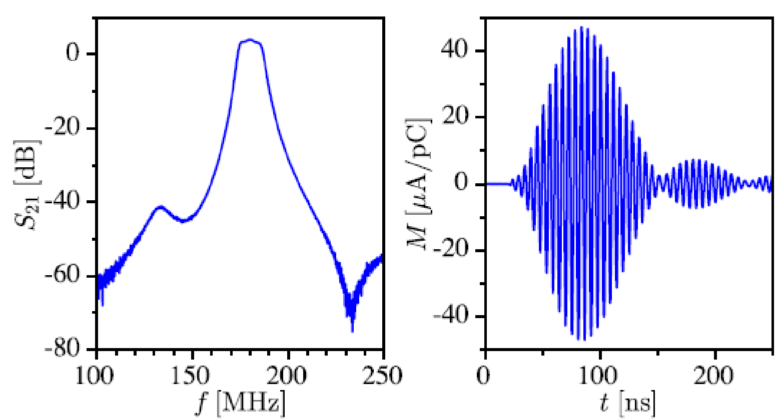
Courtesy Bergoz

SwissFEL ICT: dual-bunch resolving

- **Turbo-ICT2** (BCM-RF readout electronics)
  - High frequency transformer (bandwidth up to several hundred MHz)
  - Narrow band-pass filter centered at around 180 MHz (resonance quality factor reduced to discriminate the 2 bunch)
  - Output signal is a resonance with amplitude proportional to the bunch charge
  - Beam charge determined by measuring the apex of the resonance (sample-and-hold electronics)
  - 28 ns 2-bunch time structure discrimination and immunity to dark current
  - rms resolution 0.1 pC (1%) in the 10-200 pC SwissFEL charge range



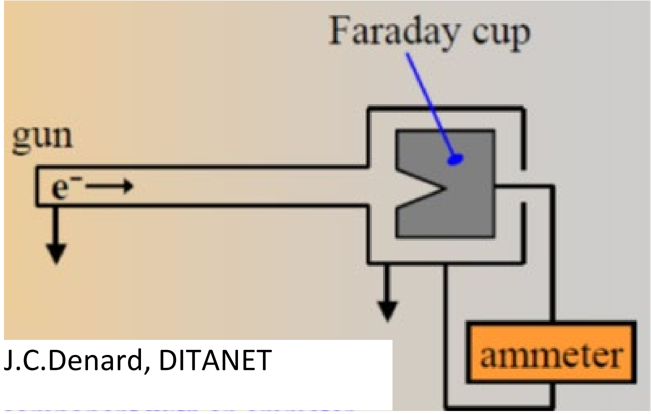
Courtesy Bergoz, Artinian et al IBIC2012



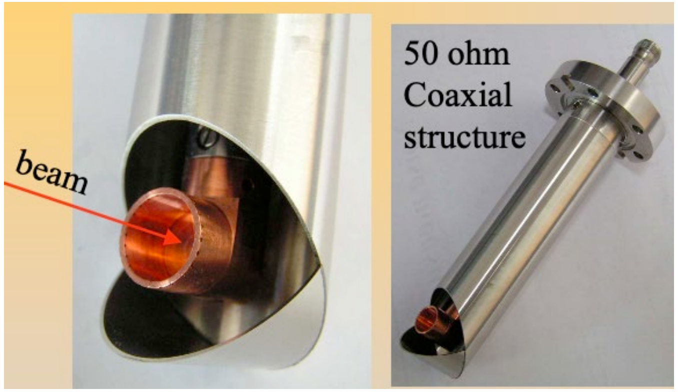
F. Stulle, J. Bergoz, Proc. FEL2015

Faraday Cup (FC)

- The Faraday cup destructively intercepts the beam
- Low current and dark current measurements
- Systematic error in charge measurements:
  - "Containment": mismatch between e.m. shower and absorber dimensions
  - "Charge trapping": absence of voltage o magnetic "cage" to bring back secondary and scattered electron
- resistor signal coupled with DC component of input current

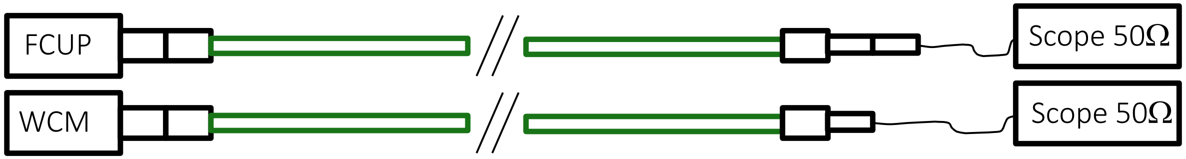


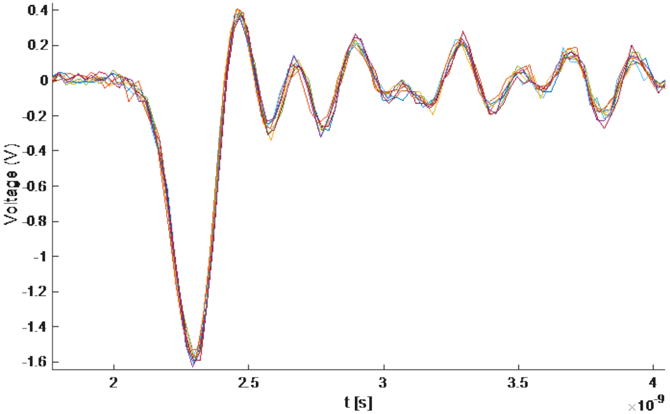
J.C.Denard, DITANET



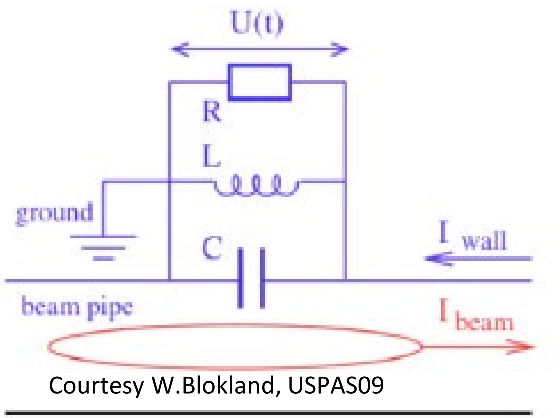
M. Dach et al. (SLS Linac) ; BIW2000

$$Q = \int \frac{v_{fcup}(t)}{R} dt$$

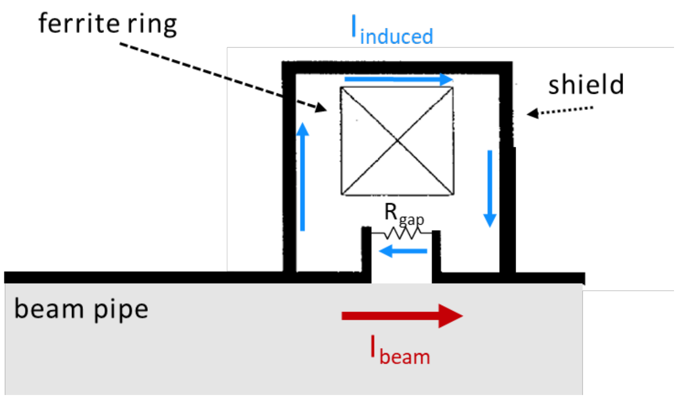




Wall Current Monitor in SwissFEL

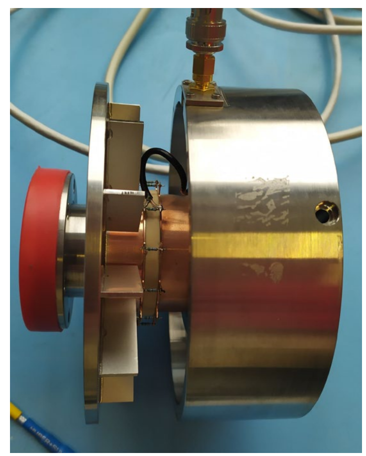


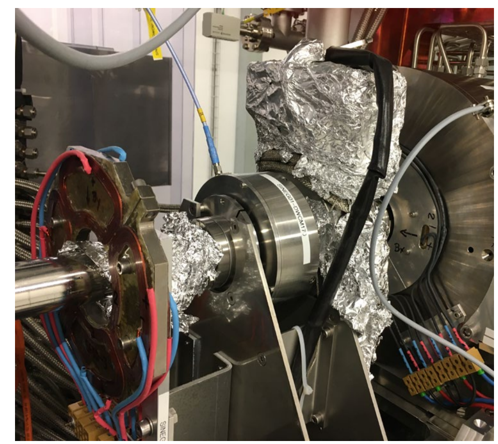
Courtesy W.Blokland, USPAS09



Prototype Wall Current Monitor
In WLHA
R_{gap} = 3.0 +/- 0.05 Ω (2.83Ω with 50Ω)
(12 x 36 Ohm gap resistors)
NiZn ferrite ring

SwissFEL Wall Current Monitor
After RF gun (z=0.58 m)
R_{gap} = ?
NiZn ferrite ring





$$Q = \frac{1}{R_{gap}} \int V_{Rgap}(t)dt$$

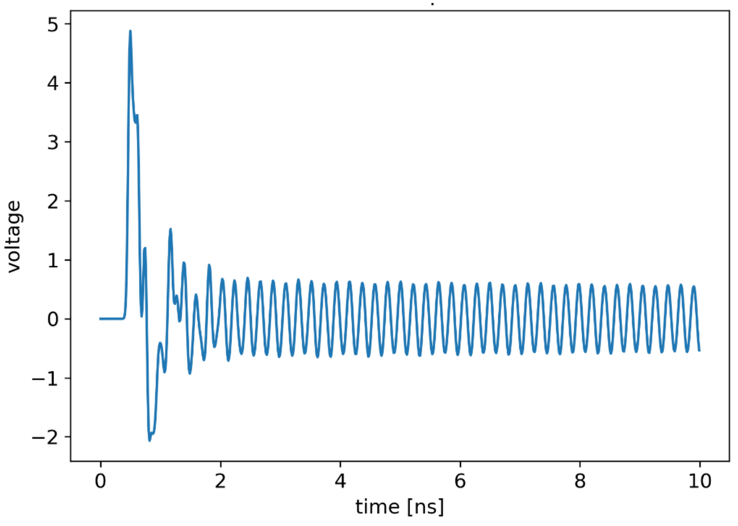
Time integration window ~ 10 ns

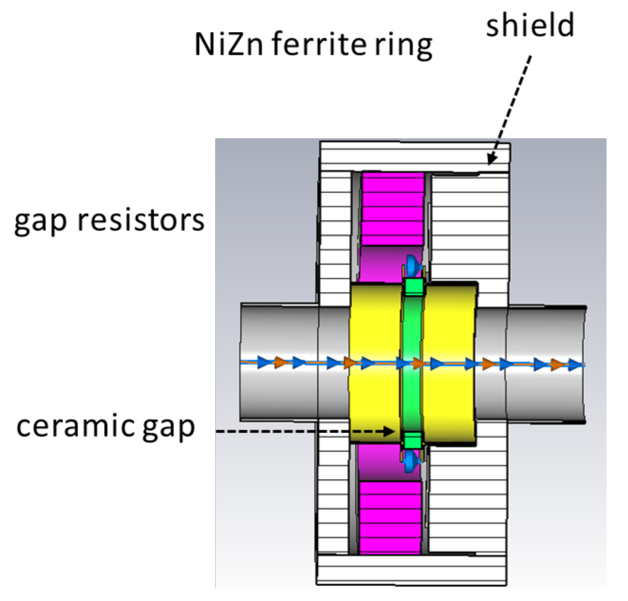
Lower cutoff frequency $f\_low = R\_gap/2\pi L$ ~200kHz (no DC component of input current measurable)

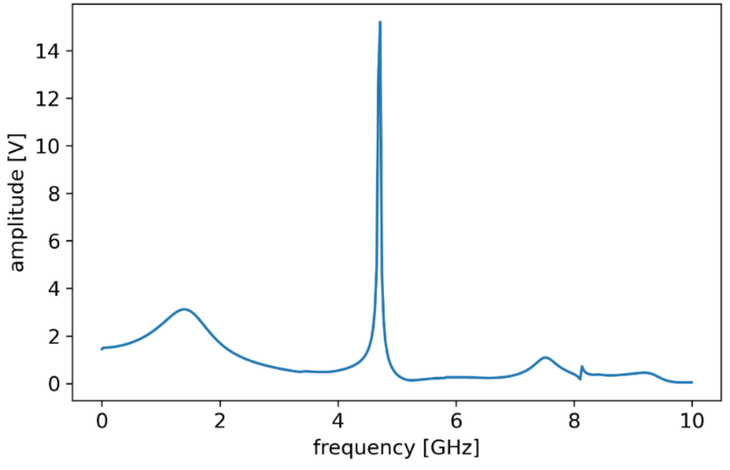
Upper cutoff frequency $f\_high = 1/(2\pi R\_gap\ C)$~GHz

good WCM➔ flat transfer impedance Z(ω)~ $Rgap$ in the frequency range of interest (up to hundreds of MHz)

CST Simulation WCM output (25 ps , 200 pC)







time response

- The Gaussian beam signal is distorted due to the upper cutoff frequency
- Voltage oscillations in the resistor (long time regime)

frequency response

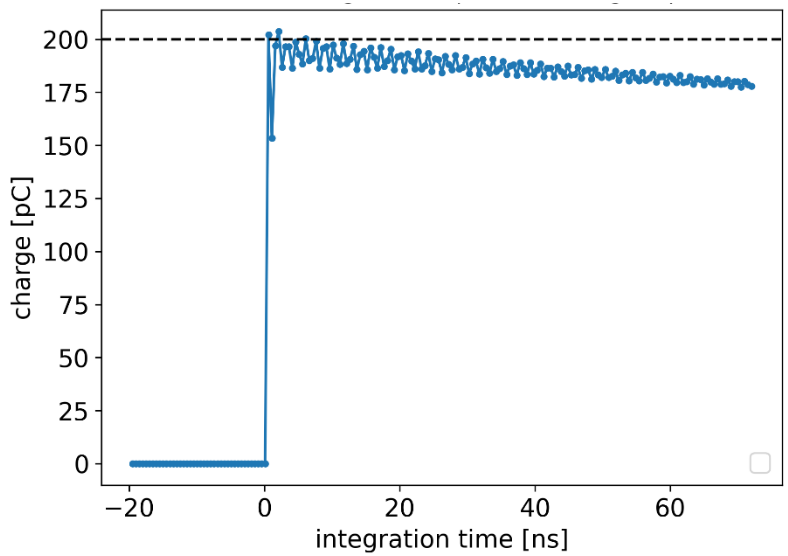
- Approx. constant for f << 1 GHz
- Broad peak at 1.5 GHz
- Sharp peak at 4.7 GHz (voltage oscillations)

1.5 Gz peak➔ mismatch of the gap resistance and transmission line capacitive gap

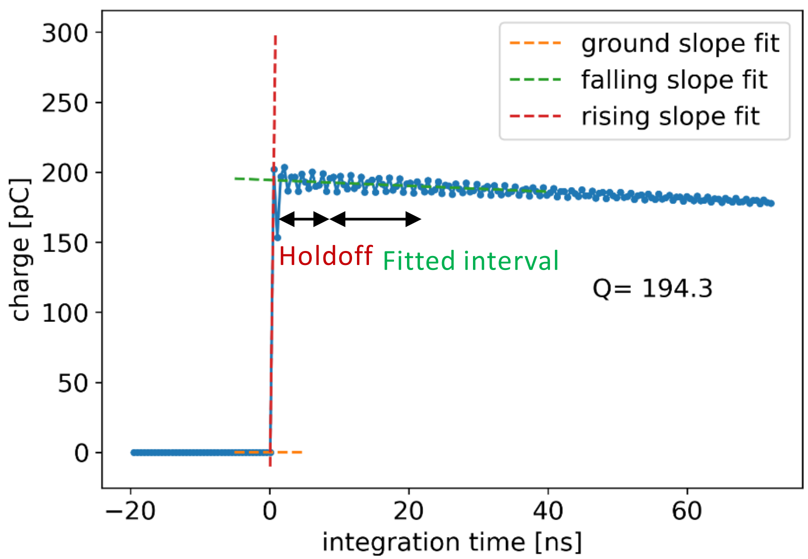
4.7 GHz sharp peak ➔ step transition (radius) from the beam pipe to the gap

Charge Measurement in the simulation

Q = 200 pC, τ=25 ps , 0.5 ns integration steps



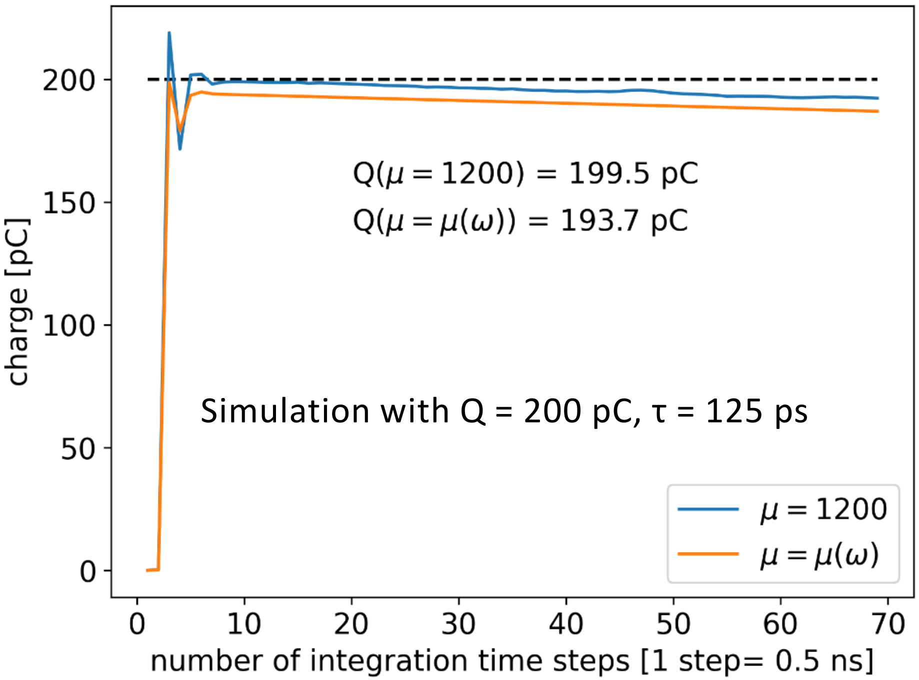
- The measured charge decreases.
  - No DC measurable. For infinite integration time, Q=0.
- The slope is determined by the lower cutoff frequency $f_{low} = \frac{R_{gap}}{2\pi L}$
- First few data points after bunch incidence include current components outside the WCM bandwidth (non measurable)

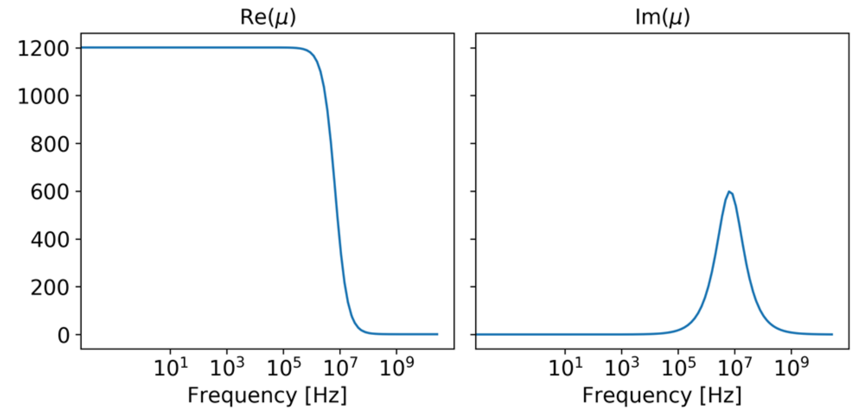


Idea: Make linear fit of slope and intersect fit with the step to reconstruct the charge at the time when the bunch arrives.

- Holdoff (2.5 ns) to avoid first few data points
- Fitted interval = 10 ns

Charge Measurement: the Ferrite Ring





Complex Inductance

$$L(\omega) = L'(\omega) - iL''(\omega).$$

The shield impedance now has a real part

$$Z_L = i\omega L = i\omega L'(\omega) + \boldsymbol{\omega L''(\omega)}$$

→ Additional frequency dependent ohmic resistor $\omega L''(\omega)$ in series with the shield inductance.

- **Dispersive ferrite yields charge losses, because we only measure the voltage over the gap**

- **Which value of the gap resistance to be used for WCM charge measurement ?**

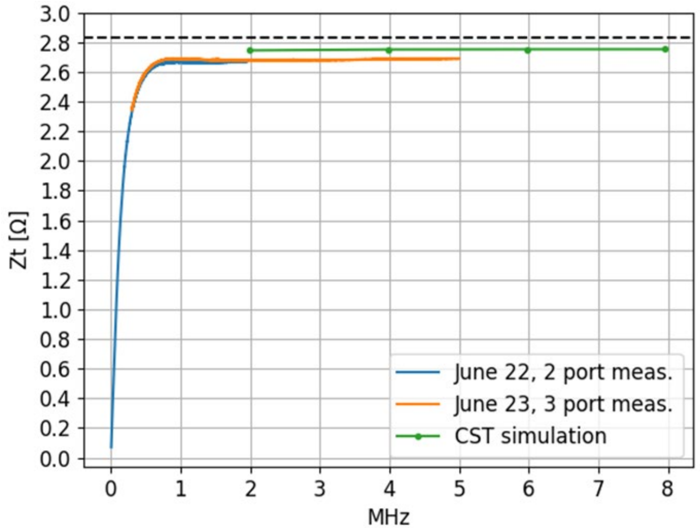
SwissFEL WCM: gap resistance value?

- Spare WCM prototype → Multimeter inspection and VNA measurements of the reflection coefficient S11 at the output port confirmed a gap resistance Rgap=3.0 Ω.

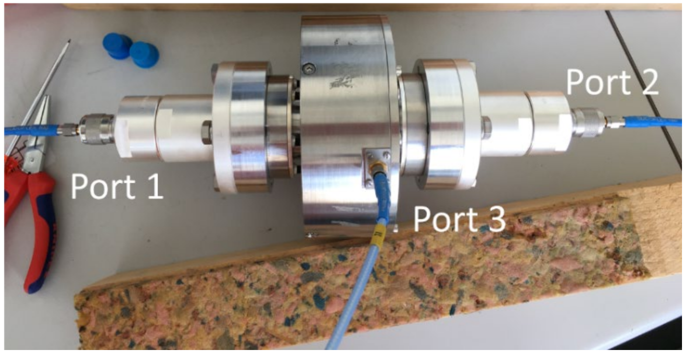
- SwissFEL WCM → No inspection possible, VNA measurements of S11 → Rgap=3.55 Ω.

- Transfer impedance measurements of spare WCM in a test-bench (coaxial wire method):
  - Transfer impedance Zt(ω) constant up to several MHz → Z(ω)~Rgap
  - Confirmed reduction of 5-6% of the transfer impedance because of ohmic losses in the ferrite Zt(ω) = 2.68 Ω instead of 2.83 Ω.
  - estimate of the ohmic resistance of the ferrite ~50.50 Ω

NB: the expected value 2.83 Ω of the spare WCM gap impedance results from the parallel of 3.0 and 50 Ω.



$$Z(\omega) = \frac{V_{out}(\omega)}{I_{beam}(\omega)} [\Omega]$$



SwissFEL WCM transfer impedance Zt(ω)?

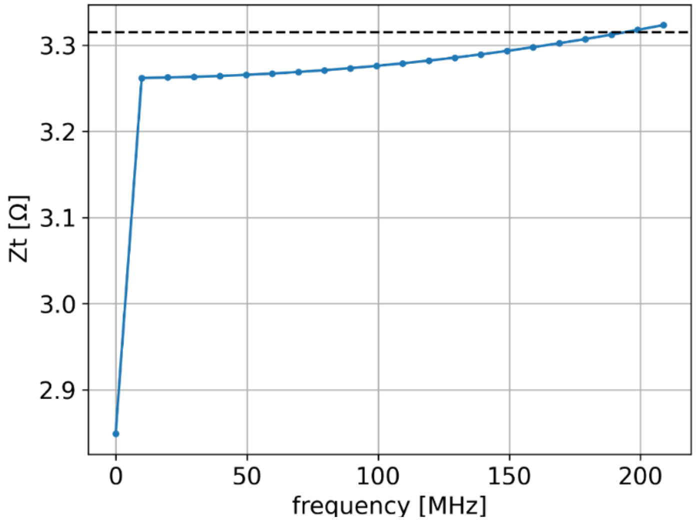
Direct measurement of transfer function of the SwissFEL WCM not possible.

Possible Solution:

- Replace the WCM currently installed at SwissFEL with the prototype WCM which is now fully characterized.
- Get Z_t from a CST simulation under hypothesis of two resistors disconnected and dispersive ferrite (Simulation parameters: Rgap = 3.31 Ω, 25 ps bunch length, Q = 200 pC)

➢ to compensate ohmic losses in ferrite instead of Rgap = 1/(1/3.55+1/50) = 3.31 Ω, the best up to date estimate of the transfer impedance are:

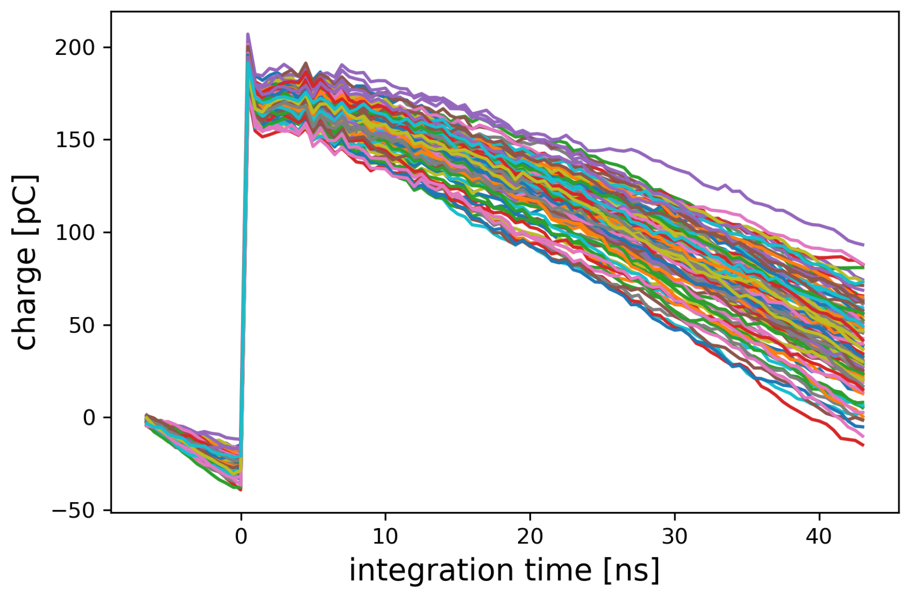
- Rt ≈ 3.26 Ω CST prediction (near-DC value of the curve)
- Rt ≈ 3.11 Ω (spare WCM VNA measurements)
- CST prediction sensitive to the permeability model of the ferrite
- To date, optimistic estimate of the incertitude on the WCM calibration parameter (Rt) about +/-5%

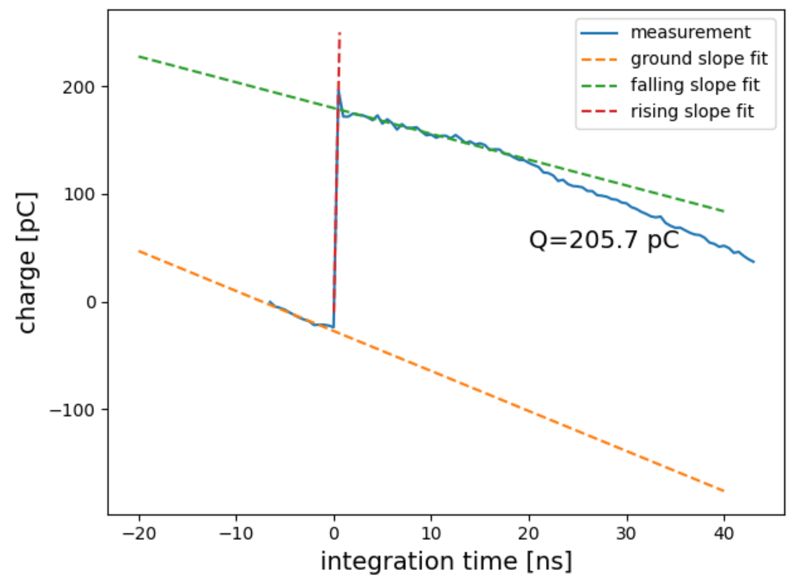


SwissFEL WCM: waveform signal integration and charge results

200 pC (charge readout of first turbo ICT)

$\boldsymbol{R_t = 3.26\ \Omega}$ (derived from SwissFEL WCM Zt simulation, considering dispersive ferrite)

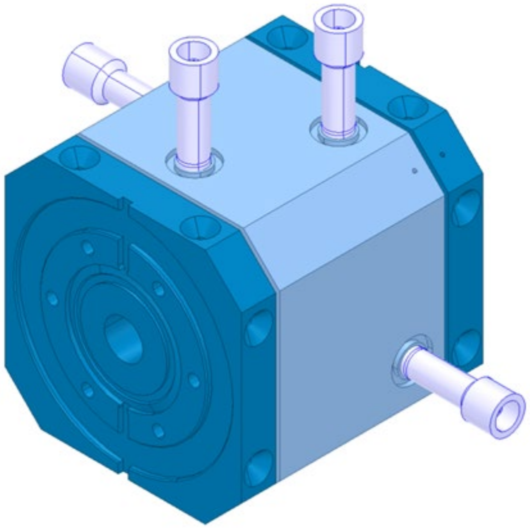




We integrate a background signal. Slopes are approximately linear.

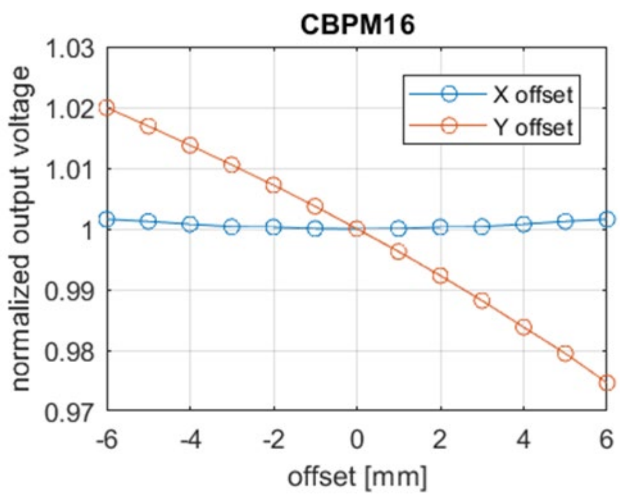
Still possible to measure the charge with our method using a linear fit!
Adapted idea: We extrapolate the charge and background signal contribution back to the time where the bunch was incident.

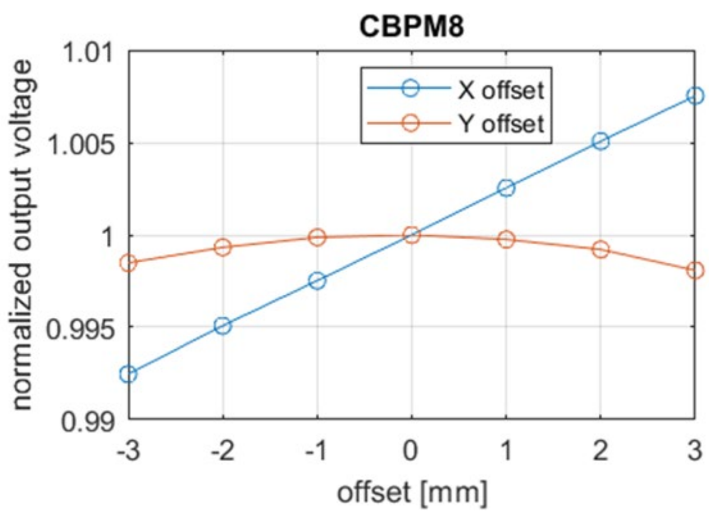
Cavity Beam position Monitor (CBPM)



- Two cavity device
- Reference cavity is designed to get an output signal proportional to the beam charge (monopole mode).
- Dependence on beam position is negligible (TM010 mode).

- We used:
- CBPM16 type (low-Q).
- CBPM8 type (high-Q)





Cavity BPM and charge measurement

BPM output signal measured with a 16GHz, 40Gs/s oscilloscope.

Bandpass filter at the BPM output to isolate the cavity fundamental mode (TM010) signal.

BPM type	TM010 frequency	Low-pass filter cutoff frequency
CBPM16	3.284 GHz	4.8 GHz
CBPM8	4.926 GHz	6.0 GHz

Voltage induced in the TM010 cavity mode and available at the cavity output port is:

$$V_{out}(t) = q\omega\sqrt{\frac{Z}{Q_e}R/Q}\,e^{-\frac{\omega t}{2Q_L}}\cos(\omega t)$$

(e.g. see : **Cavity Beam Position Monitors,** R. Lorenz)

q(charge); Z(50Ω,impedance cavity output line); ω (frequency of cavity mode TM010); R/Q (parameter depending on cavity geometry); Qe (external quality factor); QL (loaded quality factor)

For every single BPM ω, Qe and QL have been measured with VNA.
R/Q is estimated with reliable numerical codes (HFSS and CST, same result).

To better reproduce the measured signal, the expression above is also convolved with a low-pass filter function, same cutoff frequency as the filter used for measurements.

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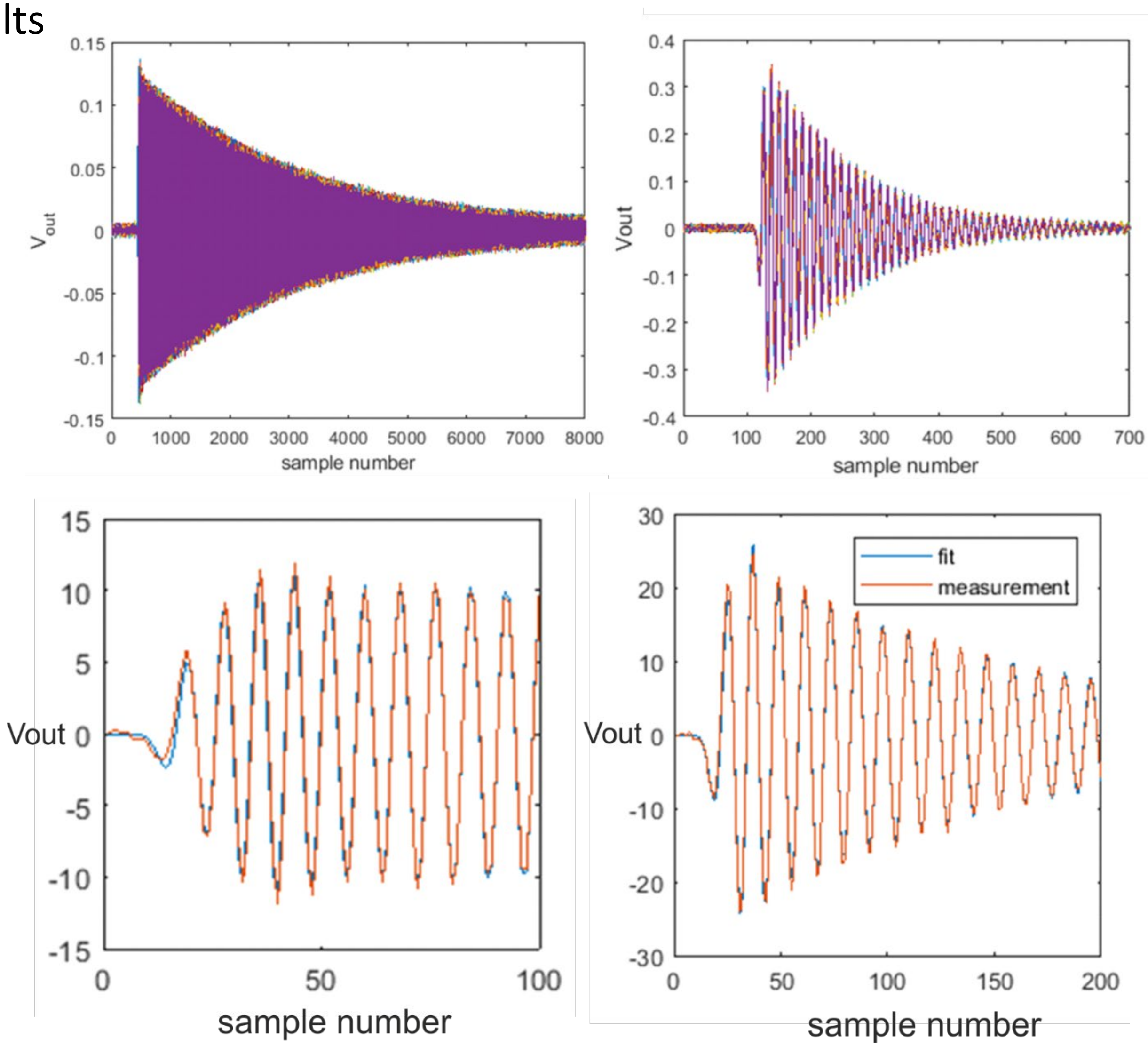
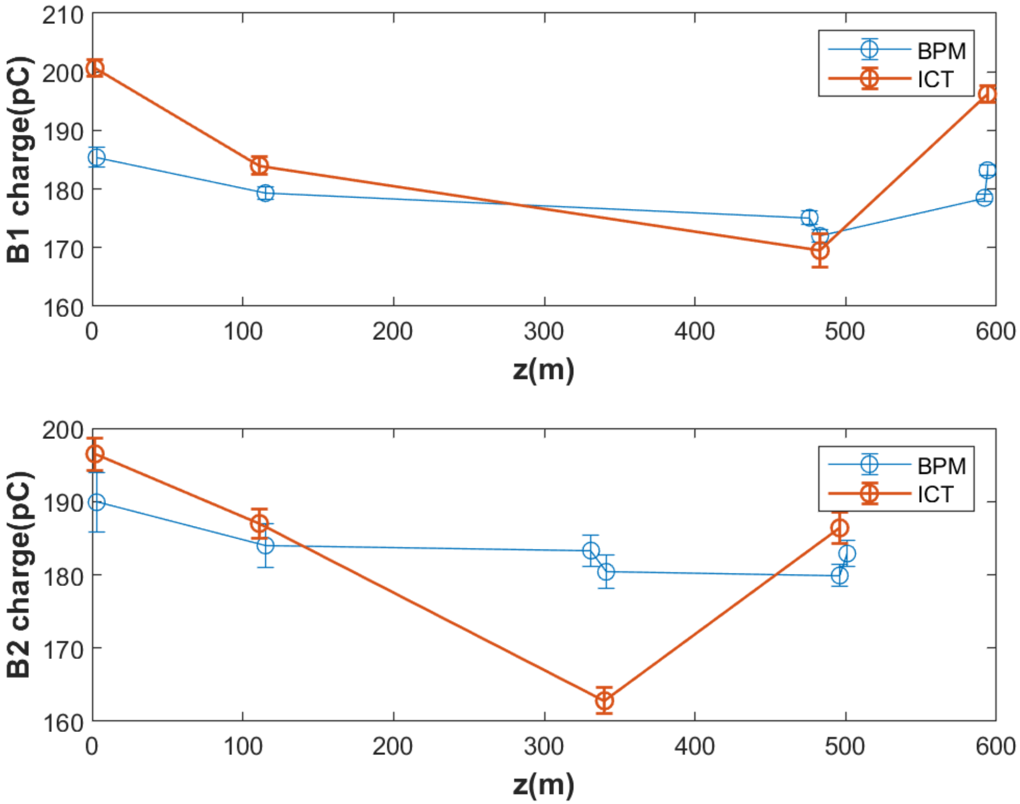
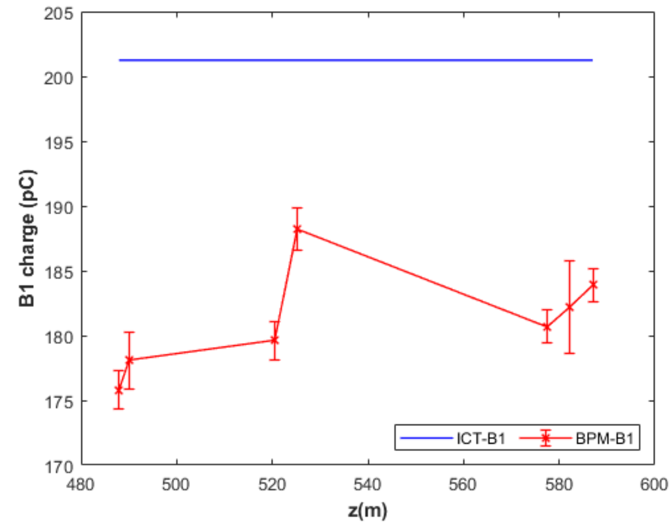
Cavity BPM charge measurements

- high Q (left) and low Q (right) BPM: waveforms measured with the oscilloscope and fit results



Beam charge measurements at SwissFEL





With respect to first ICT (~200 pC) about 20pC smaller mean charge readout from cavity BPMs:

Left (B1)➔ (10+/-3)%

Right (B1)➔ (10+/-2)%

Left: Charge measurements (B1, B2) of cavity BPMs and closest ICT in ARAMIS and ATHOS (measurements not simultaneous)

Right: charge measurements (B1) of cavity BPMs in high energy part of ARAMIS compared with average value of charge readout from the first Turbo-ICT-2 at the gun

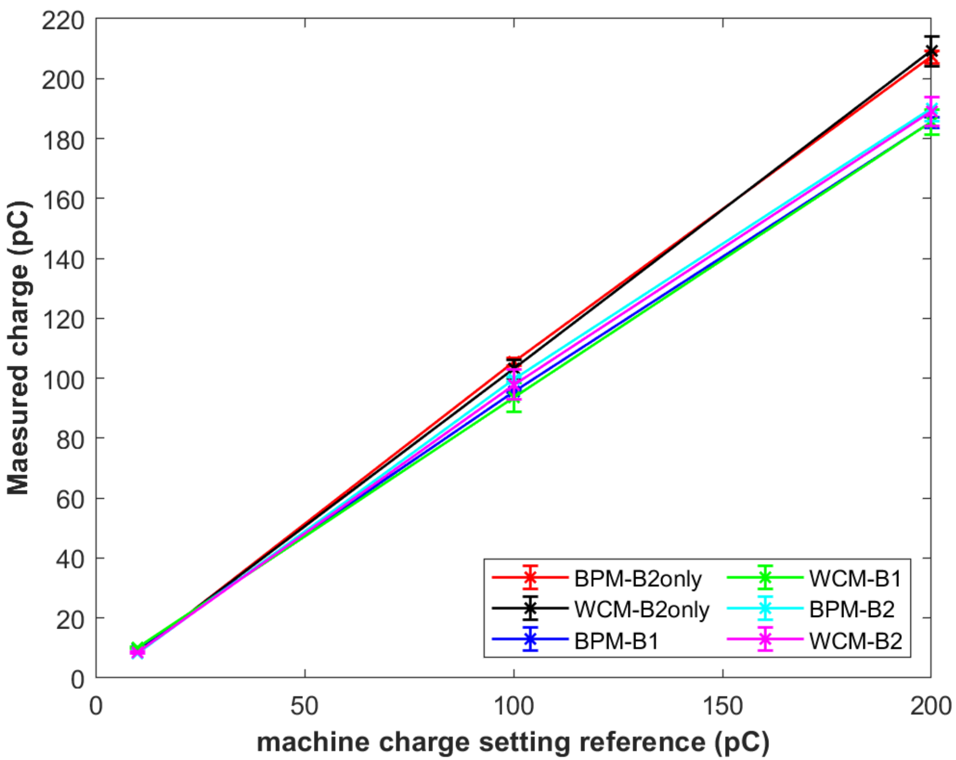
Beam charge measurements at SwissFEL

Simultaneous charge readouts of first cavity BPM and at the gun and the WCM for variable charge and three different gun settings: (1) Only bunch1; measured bunch 1 in presence of bunch-2; measured bunch-2 in presence of bunch-1.

Nominal charge	200pC	100 pC	10 pC
WCM/BPM bunch-2 only	1.0092	0.9773	1.0361
WCM/BPM bunch-1	1.0011	0.9770	1.0204
WCM/BPM bunch-2	0.9953	0.9819	1.0341

WCM transfer impedance

estimate Rt ≈ 3.26 Ω (CST prediction)



In the case bunch-1 at 200 pC, the relative percentage difference of the charge readout of the 1st cavity BPM w.r.t. the 1st ICT is about:

(8+/-1)%

Conclusions and Outlook

- **WCM**:
  - experimental characterization (VNA) and numerical modelling (CST, HFSS) but still incertitude on the calibration (+/-5%, very optimistic).
  - Further characterization needed to solve the incertitude
  - Main problem: no VNA transfer function measurements possible in the SwissFEL WCM
- **Cavity BPM**:
  - New method developed and implemented at SwissFEL for absolute charge measurements
  - Robust and statistically consistent reliability for charge measurements at SwissFEL
  - The aggregate results of the campaign of measurements with cavity BPM give us a calibration reference for alignment of all the charge monitors in SwissFEL
  - **Calibration procedure of charge monitors for bunch-1: apply a correction factor (9+/-2)%** to the charge readout measured by the first Turbo-ICT-2 at the gun and align all the other charge monitors under a condition of full transmission along the entire machine