Examination of RF Processing for Cavity BPMs

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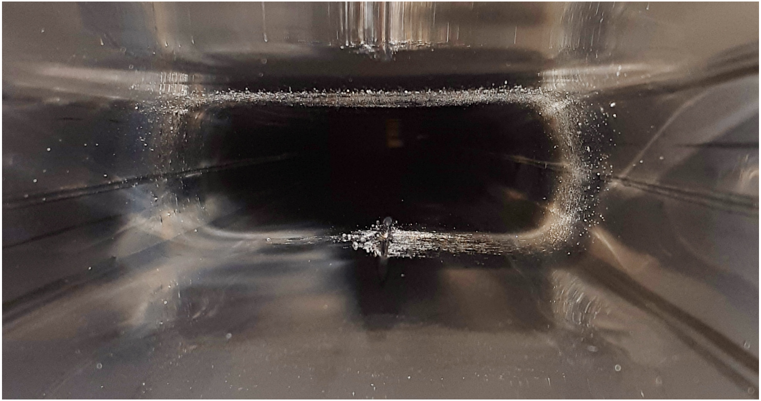
21.09.18

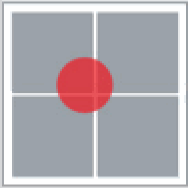
Motivation of BPMs



- Lost energy: 400 GeV in 5 ms
- Beam size: ≈ 2 x 1.6 mm
- Beam Power: 2 MW
- Cause: Wrong setting in vertical tune

BBM 33130

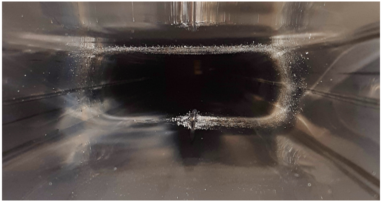
Motivation of BPMs



Feedback to align and stabilize the beam orbit

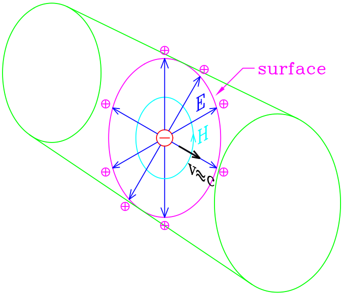
Additonal parameters

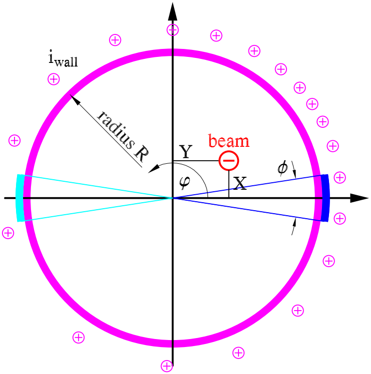
- Beam optics
- Beam tune



BBM 33130

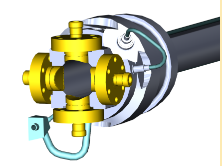
Image Current





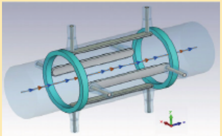
Three BPMs for CLIC

Button BPM



- $\sim 10\,\mu\mathrm{m}$
- Measuring method: image current
- Simple and robust

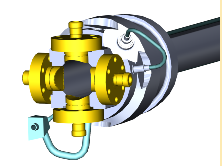
Stripline BPM



- $\sim 2\,\mu\mathrm{m}$
- Measuring method: image current
- Integrable into other structures

Three BPMs for CLIC

Button BPM



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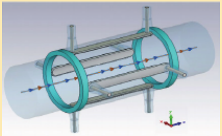
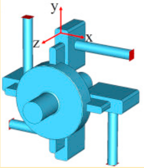


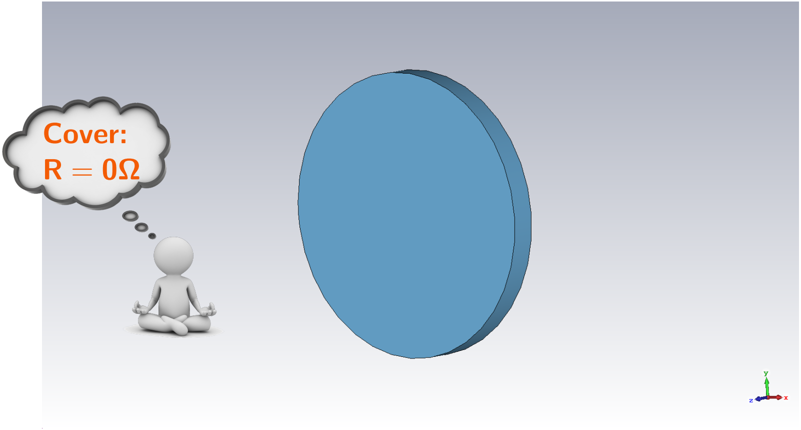
- $\sim 2\,\mu\mathrm{m}$
- Measuring method: image current
- Integrable into other structures

Cavity BPM



- $\sim 50\,\mathrm{nm}$
- Measuring method: eigenmodes
- Sophisticate adjustment

What is a cavity?



$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \mu \mathbf{j} - \epsilon\mu \frac{\partial \mathbf{E}}{\partial t)}$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{E} = 0$$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{H} = 0$$

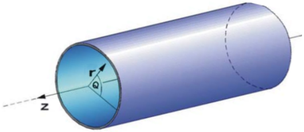
$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r})e^{i\omega t}$$

$$\mathbf{H}(\mathbf{r}, t) = \mathbf{H}(\mathbf{r})e^{i\omega t}$$

$$\nabla^2\mathbf{E}(\mathbf{r}) + \frac{\omega^2}{c^2}\mathbf{E}(\mathbf{r}) = 0$$

$$\nabla^2\mathbf{H}(\mathbf{r}) + \frac{\omega^2}{c^2}\mathbf{H}(\mathbf{r}) = 0$$

Waveguide



fz-juelich

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}(r,\varphi)e^{ikz}$$
$$\mathbf{H}(\mathbf{r}) = \mathbf{H}(r,\varphi)e^{ikz}$$

$$\nabla = \nabla_\perp + \frac{\partial^2}{\partial z^2}$$
$$k_c^2 = \frac{\omega^2}{c^2} - k^2$$

$$\nabla\mathbf{E}(r,\varphi) + k_c^2\mathbf{E}(r,\varphi) = 0$$
$$\nabla\mathbf{H}(r,\varphi) + k_c^2\mathbf{H}(r,\varphi) = 0$$

$$E_z = R_E(r)\Theta_E(\varphi)$$
$$H_z = R_H(r)\Theta_H(\varphi)$$

$$\Theta(\varphi) = A\cos(m\varphi) + B\sin(m\varphi)$$
$$R(r) = CJ_m(k_c r) + DN_m(k_c r)$$

Boundary Conditions

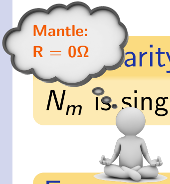
Singularity

N_m is singular at $r = 0$

→

$D = 0$

Boundary Conditions



arity

N_m is singular at $r = 0$ → $D = 0$

For $r = a$

$$H_r = 0$$
$$E_z = 0$$
$$E_\varphi = 0$$

→

TM

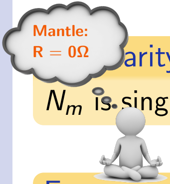
$$H_z = 0$$
$$J(k_c a) = 0$$

OR

TE

$$E_z = 0$$
$$J'(k_c a) = 0$$

Boundary Conditions



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TM

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$$J(k_c a) = 0$$

OR

~~**TE**~~

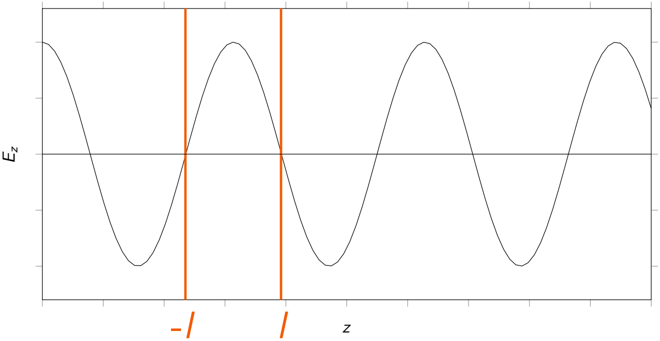
~~$E_z = 0$~~

~~$J'(k_c a) = 0$~~

Excitation through current in z-direction

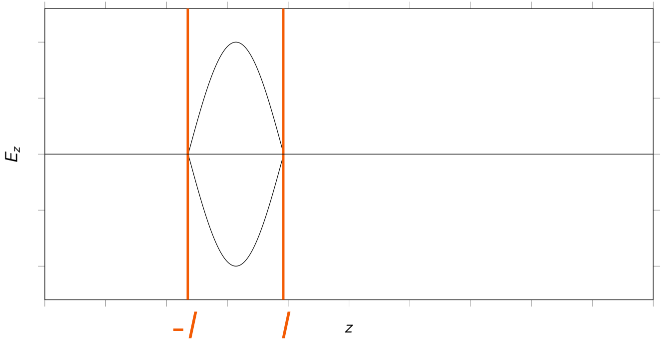
Now we make it a cavity

- Include a wall perpendicular to z at $z = \pm l$
- Produces boundary conditions: $H_z = 0, E_r = 0, E_\varphi = 0$ at $z = \pm l$
- $ae^{ik_3 z} \rightarrow A\cos(k_z z)$
- $k_z = \frac{p\pi}{l}$



Now we make it a cavity

- Include a wall perpendicular to z at $z = \pm l$
- Produces boundary conditions: $H_z = 0, E_r = 0, E_\varphi = 0$ at $z = \pm l$
- $ae^{ik_3 z} \to A\cos(k_z z)$
- $k_z = \frac{p\pi}{l}$



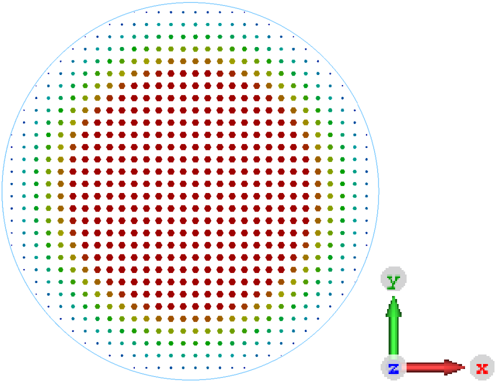
We have our Eigenmodes!!!

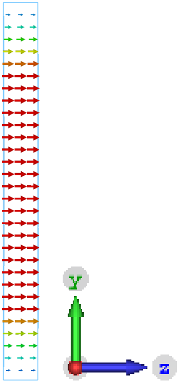
$$TM_{mnl} : E_z = E_{mn} \cdot J_m(k_c r) \cdot e^{im\varphi} \cos(ik_z z) \text{ with } J_m(k_c a) = 0$$

- m: Number of wave nodes in φ direction
- n: Number of wave nodes in r direction
- l: Number of wave nodes in z direction

TM_{010}

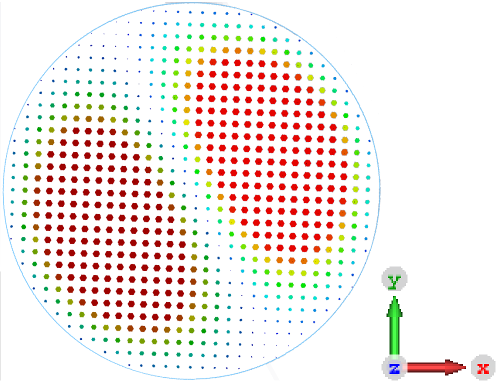
$$E_z = E_{01} \cdot J_0(k_c r)$$

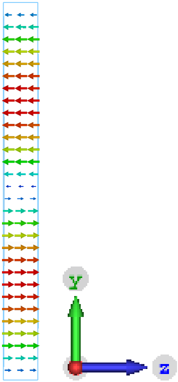




TM_{110}

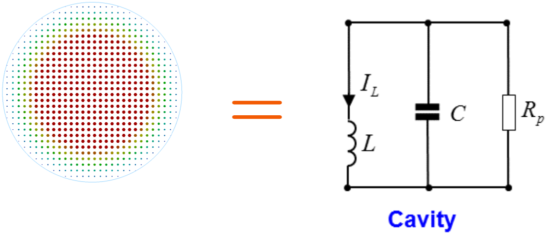
$$E_z = E_{11} \cdot J_1(k_c r) e^{i\varphi}$$





Two perpendicular polarisations

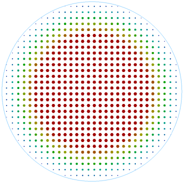
Equivalent circuit



- $U(t) = U_0 \cdot e^{-\frac{t}{2\tau}} \cdot e^{i(\omega_0 t + \varphi_0)}$
- **Decay time** $\tau = R \cdot C$: Several measurements per Bunch vs. Interaction with next bunch
- **Resonance frequency** $\omega_0 = \frac{1}{\sqrt{L \cdot C}}$: Has to be adjusted to the beam
- **Quality factor** $Q_0 = \omega_0 \tau = \frac{R}{\omega_0 L}$, high quality factor $\rightarrow$ High resolution but low resonance width.

Equivalent circuit

$Q_0 \approx 1200$



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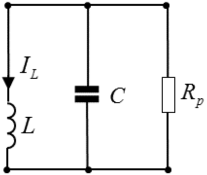

Cavity

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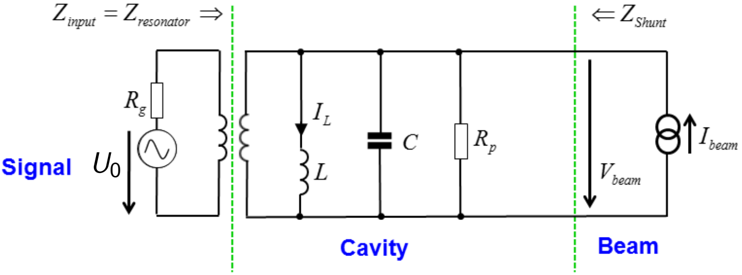
Excitation

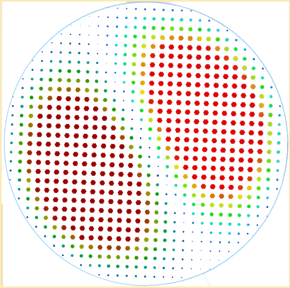


- **Shunt impedance:** $U_0 \propto Z_{shunt} \cdot I_{Beam}$
- High Shuntimpedance → large Signal but also large interaction with Beam

Shunt impedance

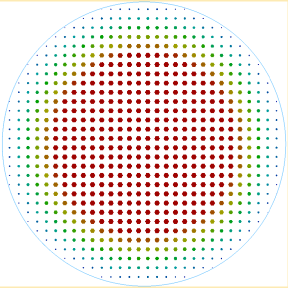
Measurement of Monopole and Dipole mode is required
$\rightarrow$ two cavities

Position Cavity



- TM_{110}
- $Z_{Shunt} \propto x$
- $E_{11} \propto I_{beam} \cdot x$

Reference Cavity



- TM_{010}
- $Z_{Shunt} = const$
- $E_{01} \propto I_{beam}$

- **C**ERN **L**inear **E**lectron **A**ccelerator for **R**esearch
- Goal: Providing a test facility at CERN with high availability, easy access and high quality bunched electron beams

https://clear.web.cern.ch/content/photo-gallery clear

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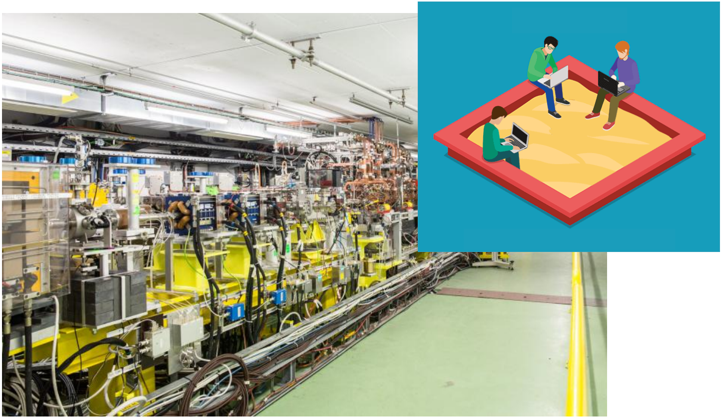
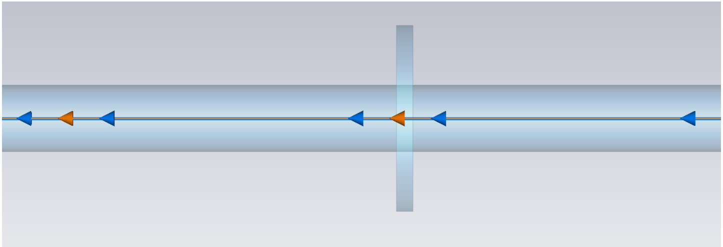
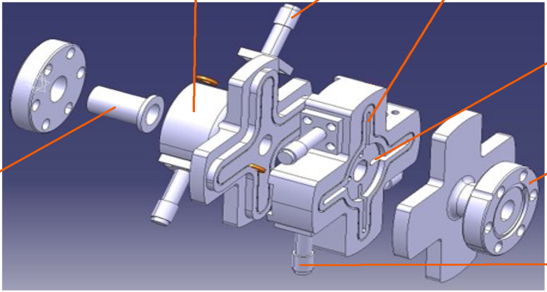


https://clear.web.cern.ch/content/photo-gallery clear

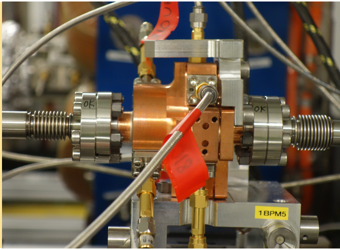
- Accelerating electrons to 130 – 220 MeV
- Bunch charge 0.01 – 0.5 nC
- Repetition rate (trains) 1 Hz
- Number of bunches in train 1 – 100
- Bunch spacing 1.5 GHz



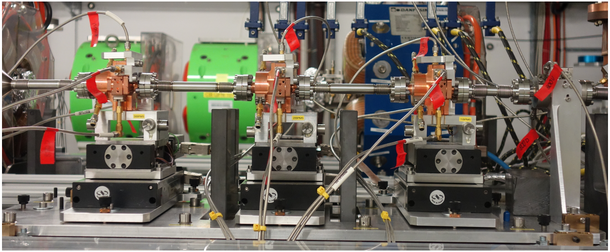
The CLIC Cavity BPM

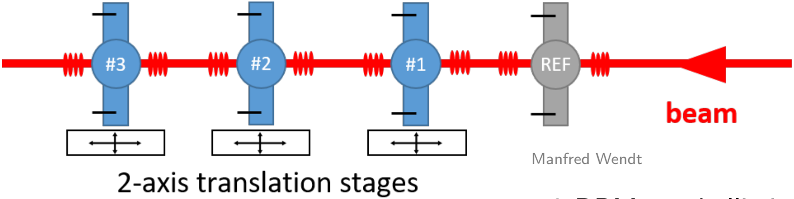


- Required for monitoring the beam trajectory in the CLIC main linac
- Resolution potential: 50 nm and 50 ns
- Adjusted to 15 GHz

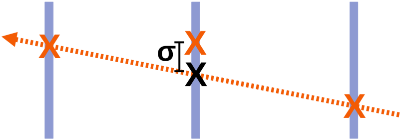


Setup At CLEAR



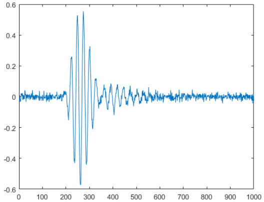


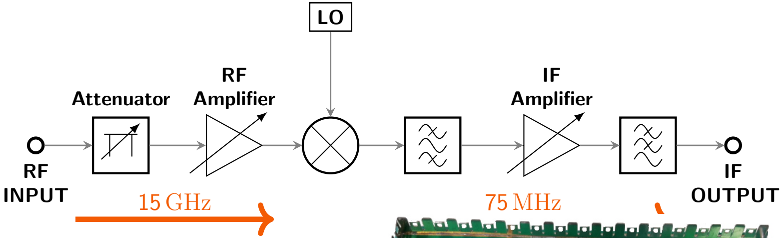
Manfred Wendt



3 BPMs on ballistic trajectory
→ measure 2
→ predict 3rd

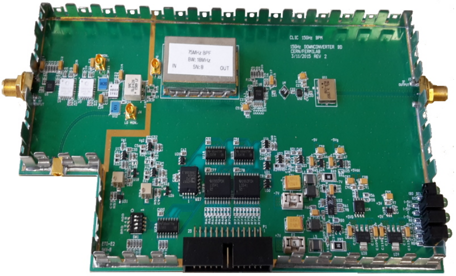
The Frontend



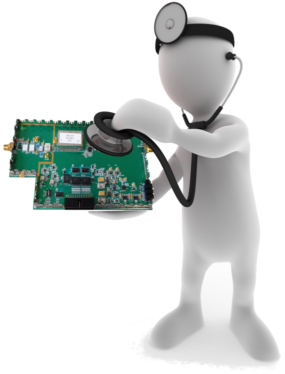


Main purpose

- Reduce the signal frequency
- Improve signal-noise ratio

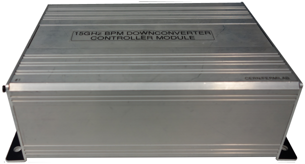


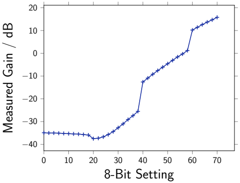
Frontend Characterization

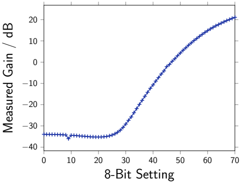


- Characterization of tunable components
- Determine gain of all components
- Determine $1\,\mathrm{dB}$ compression point to prevent saturation issues

Modification Controlling



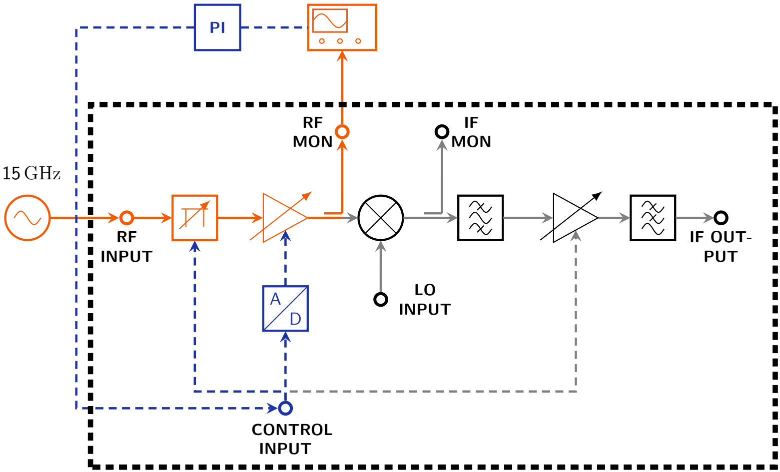




Raspbery as inexpensive alrounder

- Raspian: Preinstalled python environment for existing and planed software
- PyGPIO provides simple serial port control

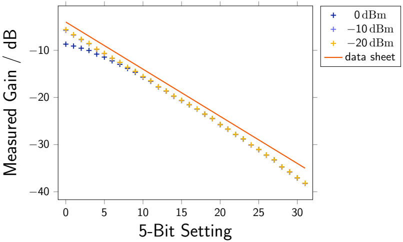
Setup RF Sector



Results RF Sector

Attenuator

- Slope follows the data sheet
- Offset due to other components



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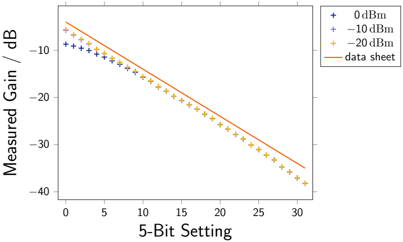
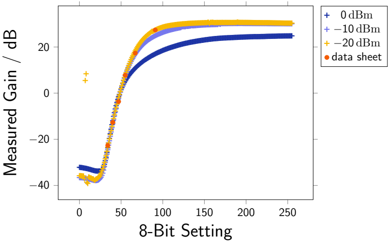
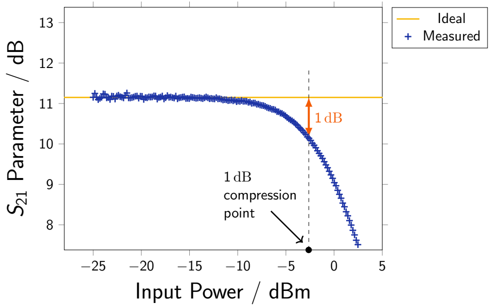


RF amplifier

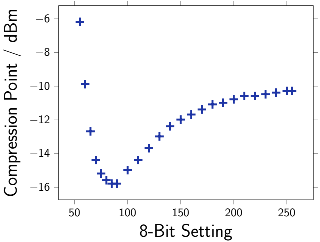
- Slope follows the data sheet
- “Prohibited” area in the beginning

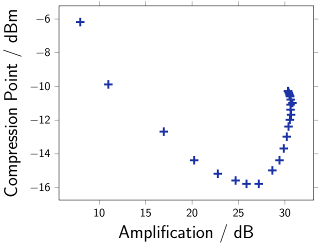


Saturation

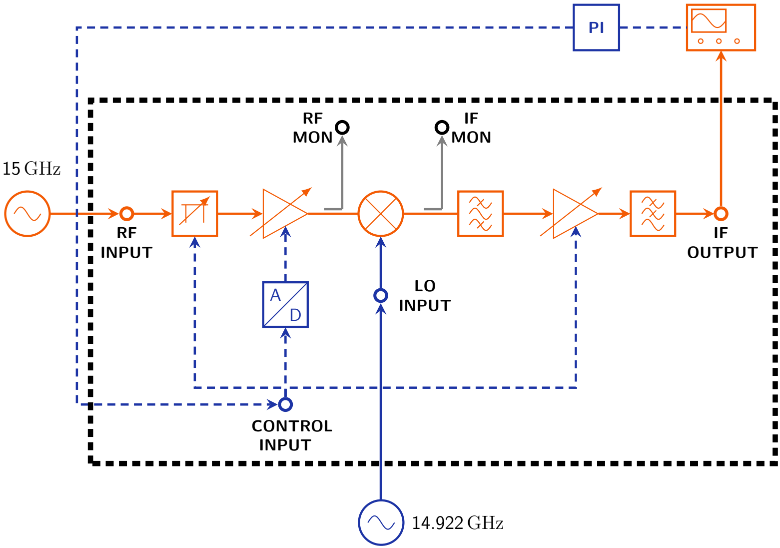


Setup
The signal generator and the signal analyzer are replaced by a VNA.

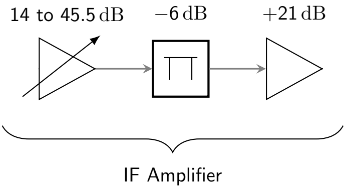


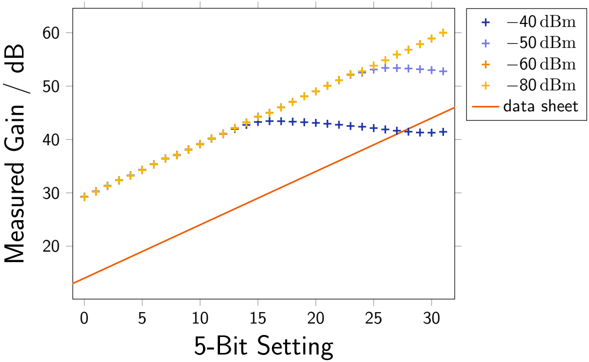


Setup IF Amplifier

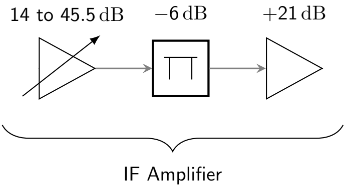


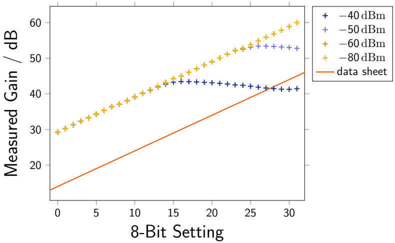
Results IF Amplifier

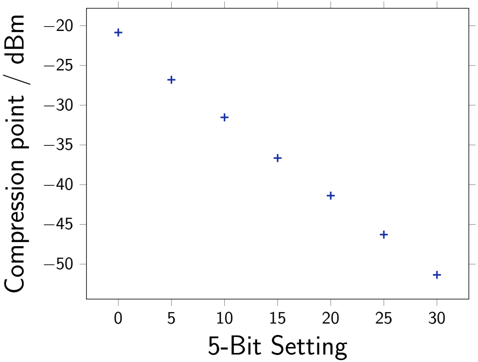




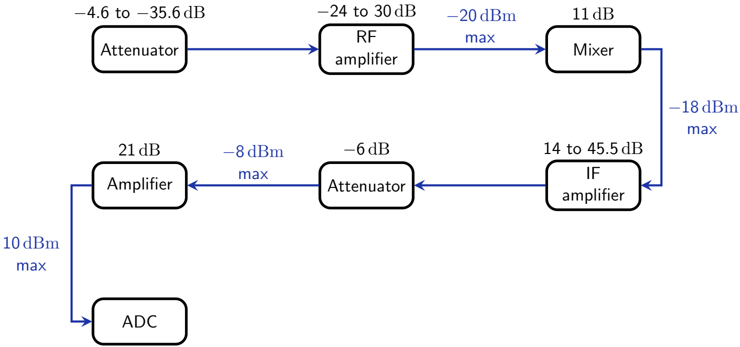
Results IF Amplifier







Summary

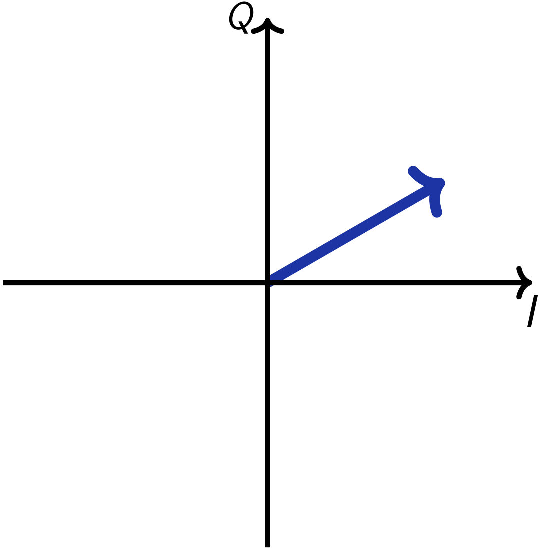


- Results are fed into a Pyhton script
- Input power is determined
- Best settings are set

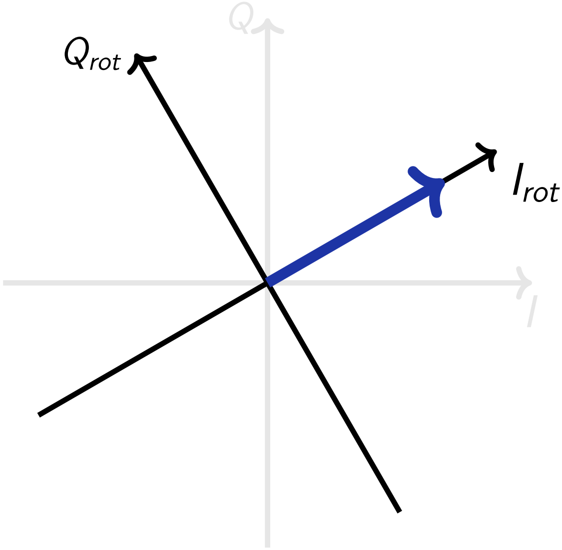
Beam Measurments

- Goal: Get the resolution of the system
- Two sessions
  - November 2017
  - June 2018
  - September 2018

Calibration

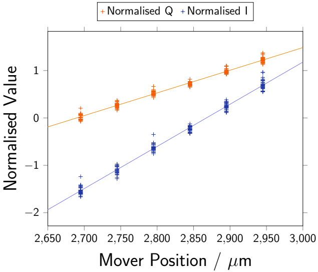


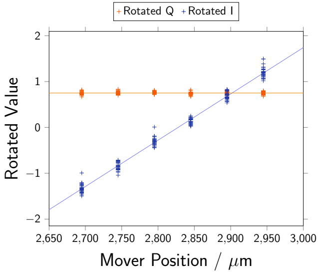
Calibration

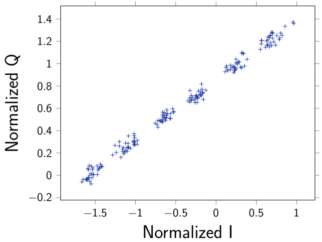


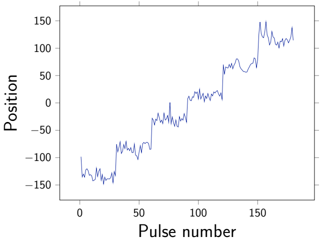
Calibration

- Each measurement set consists of 6 calibration and one resolution measurement



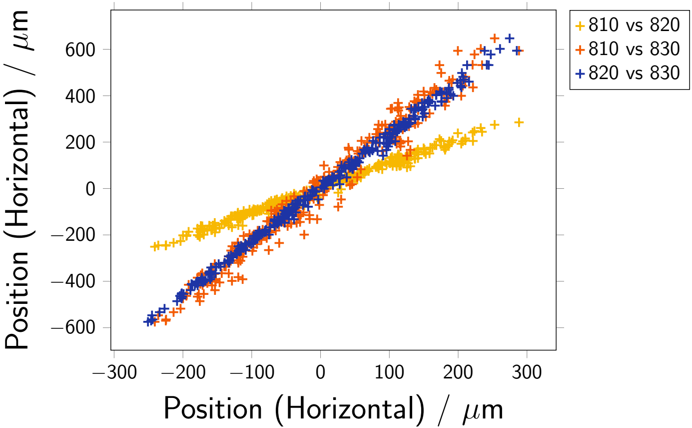






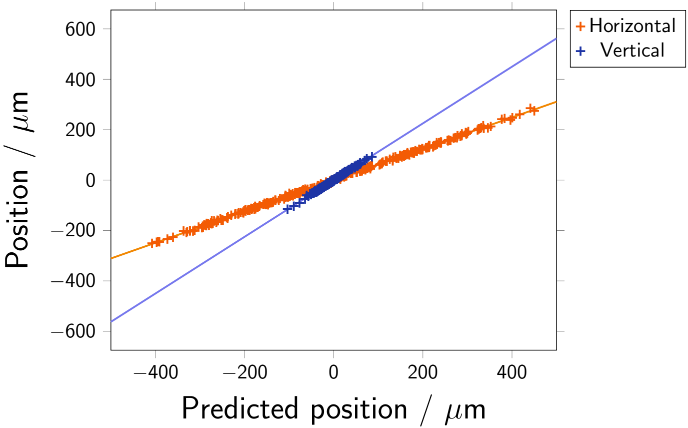
November 2017 - Correlation

- Single bunches with 19 pC



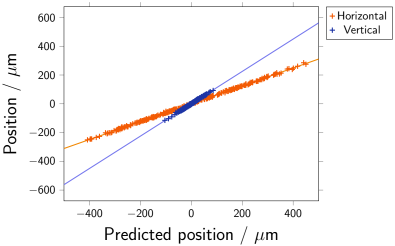
November 2017 - Prediction

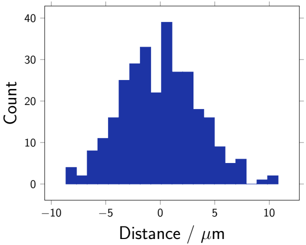
- Single bunches with 19 pC

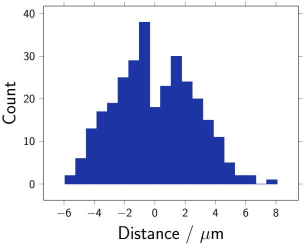


November 2017 - Resolution

- Single bunches with 19 pC

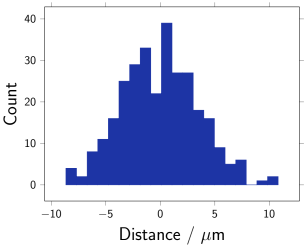


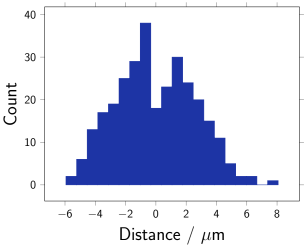




November 2017 - Resolution

- Single bunches with 19 pC
- Attenuation of up to 55 dB

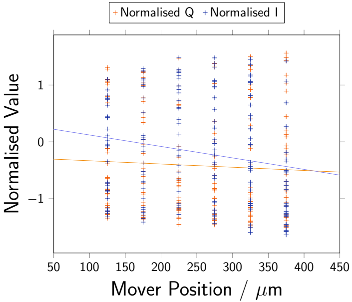


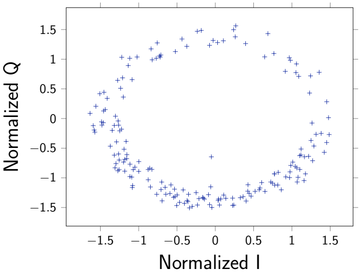


Settings	Horizontal resolution / μm	Vertical resolution/ μm
ATT 16, RF 24, IF 0	19.69	4.57
ATT 16, RF 24, IF 5	3.48	2.60
ATT 0, RF 0, IF 15	13.95	3.09

June 2018 - Modifications

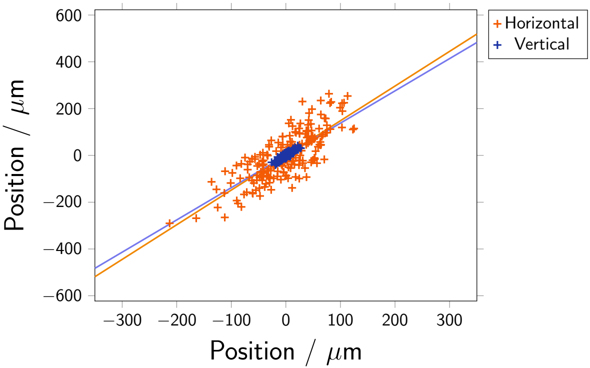
- Single bunch with around $1\,\mathrm{pC}$ to decrease required attenuation
- Different settings for each channel
- Unintended: Failing BPM 830





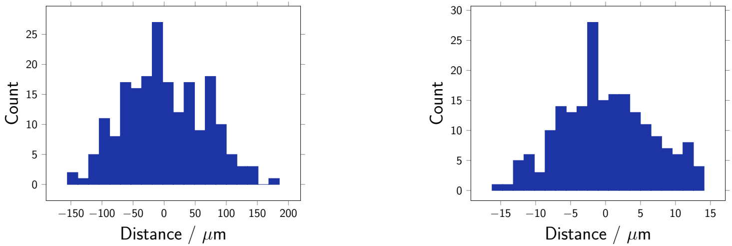
June 2018 - Correlation

- Single bunch with around $1\,\mathrm{pC}$ to decrease required attenuation
- Different settings for each channel
- Unintended: Failing BPM 830



June 2018 - Resolution

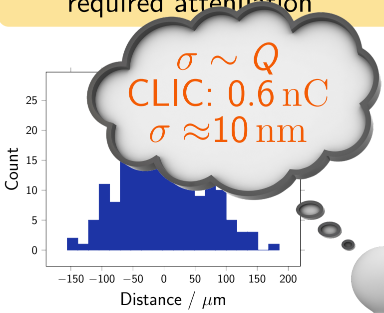
- Single bunch with around $1\,\mathrm{pC}$ to decrease required attenuation

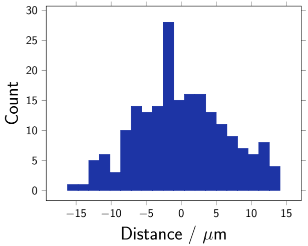


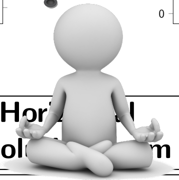
Measurement	Horizontal resolution / μm	Vertical resolution/ μm
1	64.88	6.41
2	28.62	20.26
3	1029.60	144.69

June 2018 - Resolution

- Single bunch with around 1 pC to decrease required attenuation



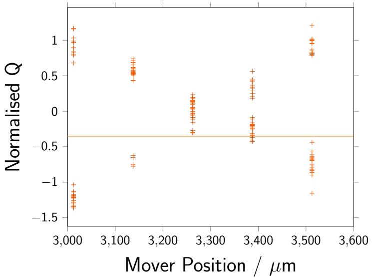


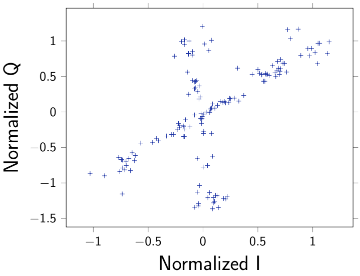


Measurement	Hori[illegible]l resol[illegible]m	Vertical resolution/ μm
1	64.88	6.41
2	28.62	20.26
3	1029.60	144.69

September 2018 - Calibration

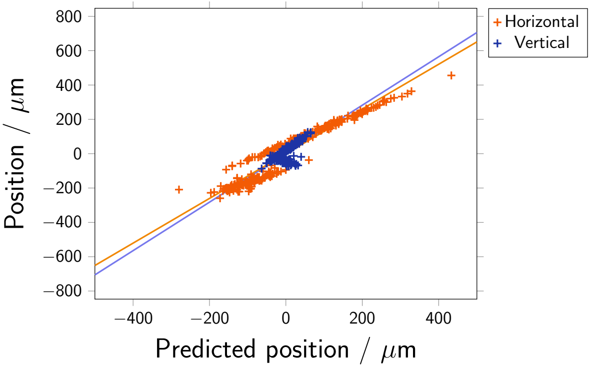
- Single bunch with around 0.7 pC to decrease required attenuation
- After some replacements 3 working BPMs
- Binary jitter





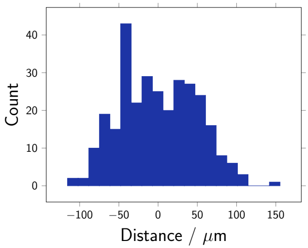
September 2018 - Results

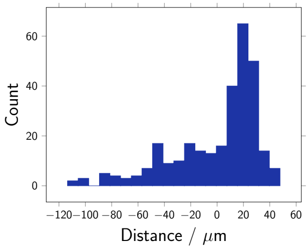
- Single bunch with around $0.7\,\mathrm{pC}$ to decrease required attenuation
- After some replacements 3 working BPMs
- Binary jitter



September 2018 - Results

- Single bunch with around 0.7 pC to decrease required attenuation
- After some replacements 3 working BPMs
- Binary jitter





Measurement	Horizontal resolution / μm	Vertical resolution/ μm
1	96.58	20.15
2	36.62	30.60

Summary

- Electronics is characterized
- Resolution of 2.6 $\mu\mathrm{m}$ was achieved
- Proved pickup quality
- Additional software was written
  - Automated gain measurements
  - Best settings with current setup

- Modify electronics
  - Ensure radiation hardness
  - Allow higher signal power
- Write GUI for control room

MERCI
THANKS
DANKE