Manfred Wendt (CERN)

FCC-ee BPMs: Required BPM Precision for FCC (?)

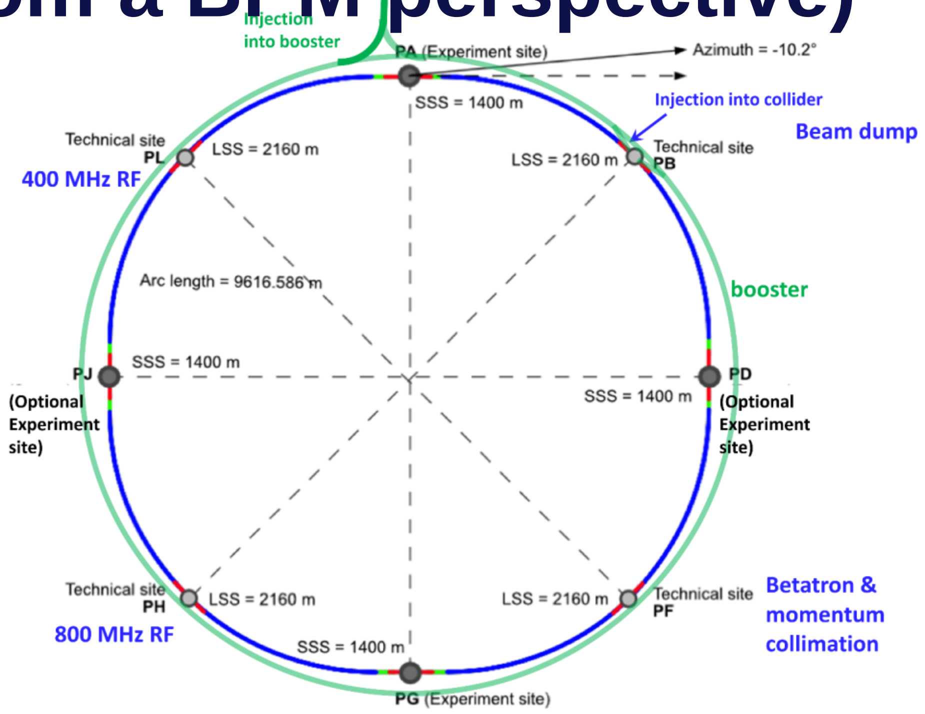
with contributions from many colleagues

Outline

- FCC-ee from a BPM perspective
- Definition of Measurement Terms
- FCC-ee BPM R&D Status
- Challenges of the FCC-ee BPMs
- BPM Requirements
- BPM R&D Activities
- BPM Operational Principle
- Button-Style BPM Characteristics
  - *Beam position, BPM signals, resolution, tolerances and BPM offset, EM pre-alignment*
- Next Steps
- Discussion

FCC-ee in a nutshell (from a BPM perspective)

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
circumference [km]	91.18
max. beam energy [GeV]	182.5
max. beam current [mA]	1280
max. # of bunches/beam	10000
min. bunch spacing [ns]	25
min./max. bunch intensity [10^{11}]	? / 2.43
min. H geometric emittance [nm]	0.71
min. V geometric emittance [pm]	1.42
min. H rms IP spot size [μm]	8
min. V rms IP spot size [nm]	34
min./max. rms bunch length [mm]	1.95 / 14.5

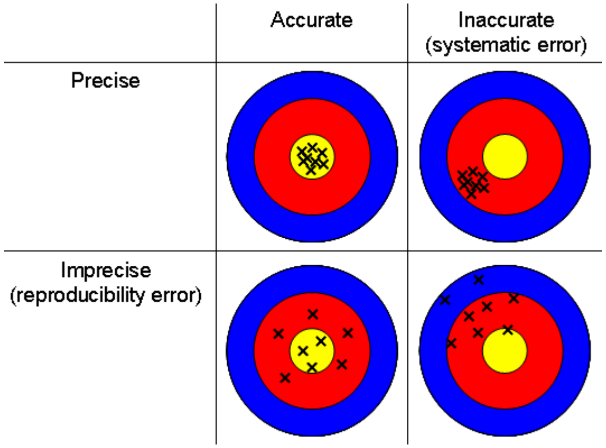


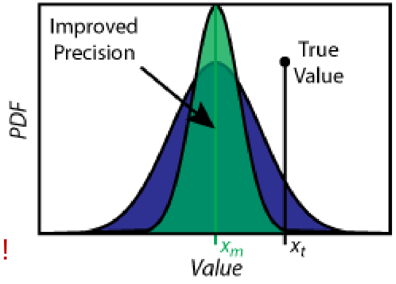
+ injectors and positron source

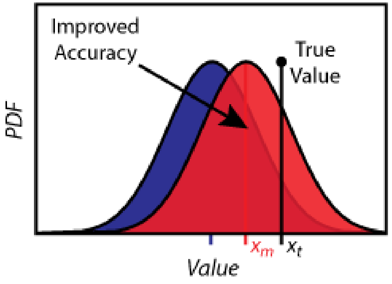
K. Oide, J. Gutleber

Definition of Measurement Terms

- **Accuracy**
  - ***How close is our measured value to the true values?!***
    - Sometimes we distinguish between absolute and relative accuracy.
    - Typically limited by mechanical and electronics offsets, gain & calibration factors, non-linearities ⇒ **absolute and relative accuracy**
    - **Offsets** in BPMs play a particular and important role
      - *The electromagnetic offset between BPM and quadrupole symmetry axis is more relevant that the mechanical offset*
- **Precision**
  - ***How good can we reproduce our measurement?!***
    - Temperature drift and other environmental effects, aging of components ⇒ **precision**
- **Resolution**
  - ***What is the smallest change of the true value we can detect with our measurement apparatus?!***
    - Bandwidth, input amplifier noise, power supply ripple, ADC clock jitter and ENOBs ⇒ **resolution**
- **Precision vs. resolution?!**
  - ***Almost the same thing, except for the time scale***
    - Definitions vary in literature; this is my personal definition!
      - *https://meettechniek.info/measurement/accuracy.html*







Foreword: Status of FCC-ee BPM R&D

- **BPM R&D activities have not yet started in the CERN BI group**
  - ***Started to collect information at the various meetings and workshops***
  - ***Looked at the real estate near the quadrupole***
  - ***Started discussions with other teams, e.g., beam dynamics, EPOL, vacuum, magnets, etc.***

- **FCC-ee BPM pickup design activities**
  - ***Dedicated PhD activity in collaboration with University of Oxford (starting early 2023)***
  - ***Cover all design aspects of the BPM pickup***
    - *BPM requirements, beam parameters*
    - *Wakefield / impedance, RF heating, trapped eigenmodes, etc.*
    - *Integration, mechanics, tolerances, UHV feedthroughs, radiation aspects, position non-linearities*
    - *Calibration, mass production, costs,…*
    - *Prototyping, laboratory measurements, beam studies, expected performance…*

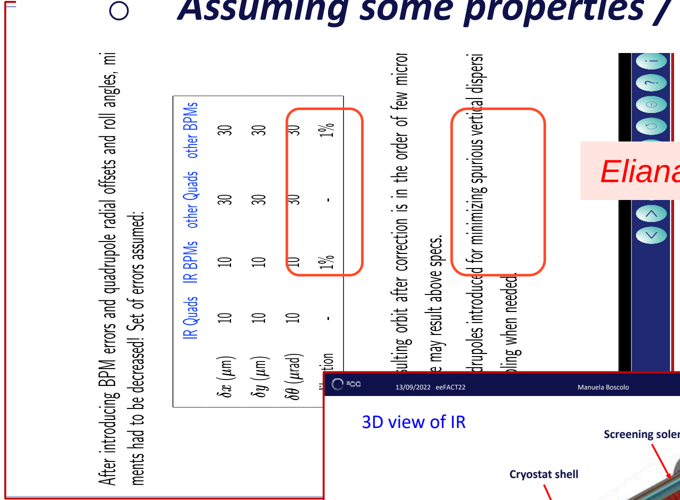
- **BPM requirements**
  - ***E.g., precision, accuracy, etc., cannot be defined by the BI team***
  - ***The BI team will try to meet the requirements given by beam dynamics, EPOL, operations, etc.***
  - ***This presentation give some background about limits and possibilities.***

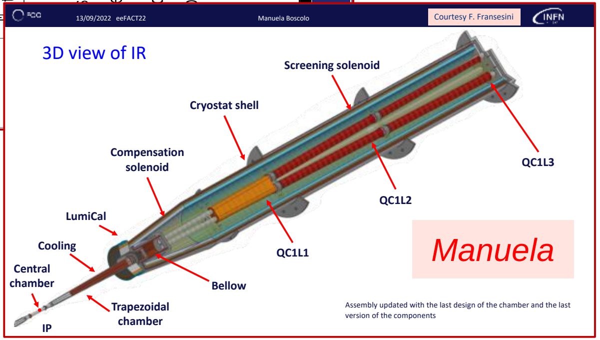
Beam Position Monitors (BPM)

- A total of ~6000 BPMs in the 92 km tunnel
  - *2000+2000 BPMs for the main rings, 2000 BPMs for the booster ring*
  - *Orbit, turn-by-turn, and bunch-by-bunch operating modes, 25 ns signal processing time*
- BPMs and BPM pickups also will be used for various non-orbit applications
  - *Tune measurement, orbit and bunch FB, timing electrodes, instability monitor, etc.*
- Some of the many challenges (beside communication, budget, organization,…)
  - *Large scale system: infrastructure, segmentation, cost optimization*
  - *Signal latency (for FB apps), synchronization of turn and bunch data, large data throughput (probably >20 GSPS for each BPM plane) and decimation*
  - *Radiation tolerant tunnel hardware*
  - *Low beam-coupling impedance of the BPM pickups (wakefields)*
  - *Alignment and stabilization (temperature variation) of the BPM pickups*
  - *Accuracy (non-linearities), resolution (orbit, TxT, BxB), precision (drifts, aging) requirements, which are similar or even more tight then last gen SL sources.*
  - *Different types of BPMs, e.g. in the arcs, near the IPs (MDI)*

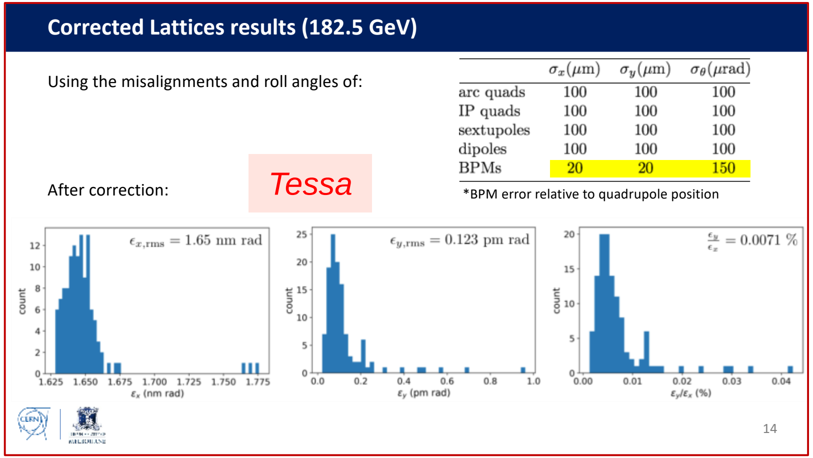
BPM Requirements (1)

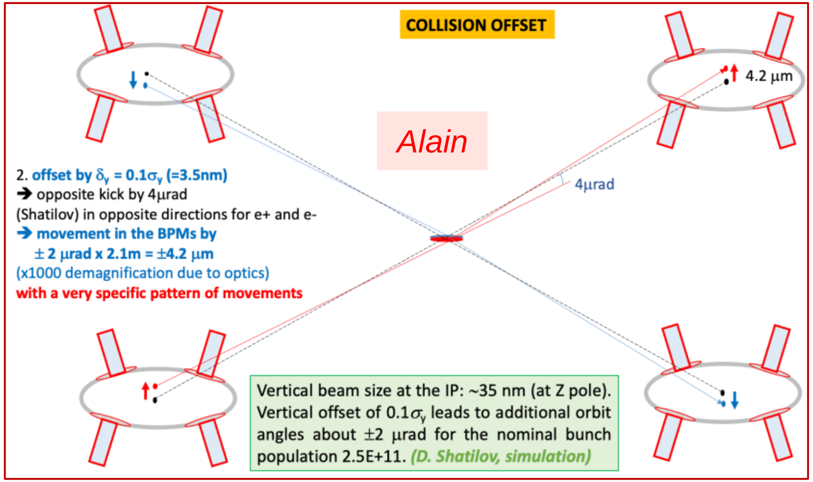
- **BPMs are popping up in various FCC-ee talks and presentations**
  - ***Assuming some properties / requirements***





…but where are the IR BPMs?!





BPM Requirements (2)

Dispersion measurement

FUTURE CIRCULAR COLLIDER

- Dispersion measurements for non-colliding beam is easily done by a shift of RF frequency, for instance.
- However, it is only possible at low current. We cannot store non-colliding high current beam without collision due to instabilities. → E. Carideo
- Measurement for colliding bunches will be very difficult, as it violates the collision conditions to cause the 6D flip-flop.
- String high current also changes everything: orbit, optics, dispersion, etc.
- The only possibility is to measure the dispersion by exciting the synchrotron motion of the pilot bunches, by special deflector (either longitudinal or transverse at a dispersive location).

Top-up injection

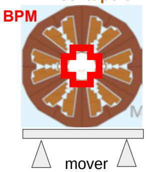
FUTURE CIRCULAR COLLIDER

- The top-up injection shakes the colliding bunches periodically, transversely or longitudinally.
- Then either the bunch-by-bunch or narrowband feedbacks tries to damp such oscillations. Esp. the narrow band feedback shakes the pilot bunches.
  - The magnitude must be estimated.
- Such disturbance on the pilot bunches may affect the spin tune measurement.
- It is not possible to suspend the injection, since the delicate balance between two or *four* colliding bunches easily breaks to result in unrecoverable 6D flip-flop.

Oide-san

K. Oide, Sep. 19, 2022 11

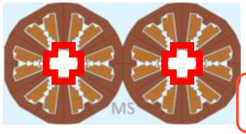
Attach BPMs to sextupoles in FCC-ee? Movers?



Prealignment without beam could be kept to ~100 μm.
With beam, a high accuracy BPM (<1μm) attached to the sextupole with magnetic centers aligned to <1μm level (sext. temperature and powering to be considered).

Ideally mover range ~0.5mm (step <1μm) remotely used to keep sextupole centered to the beam (helped with orbit correction) within 1μm.

Rogelio



Same prealignment and BPM concept as in IR?
Have to mostly rely on orbit correction. Movers?
Keep 1-10μm beam centering accuracy?
This solves the disruption from chromaticity correction.

BPM: Turn-by-turn capabilities will be fundamental to allow fast measurements at high intensity (res. ~ 10μm)

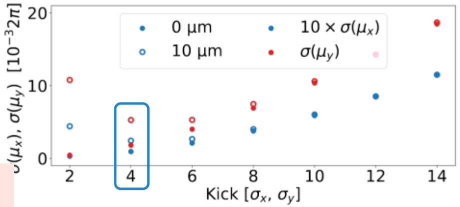
Kick Strength and Phase Advance

- Relative rms phase advance error with respect to the model used for defining the quality of TbT measurements
- First TbT tracking over 500 turns for FCC-Z mode and 360 installed BPMs
- Without synchrotron radiation
- Gaussian BPM noise applied

FCC-Z mode
500 turns, no synchrotron radiation
Minimum hor and ver. phase advance error with 10 μm BPM noise: 0.24 x 10^{-3} (2π) and 5.28 x 10^{-3} (2π)

Comparison LHC
6600 turns, AC-dipole
Minimum hor and ver. phase advance error, ~100 μm BPM noise: < 1 x 10^{-3} (2π)

FCC-Z mode at 45.6 GeV single particle tracking



Jacqueline

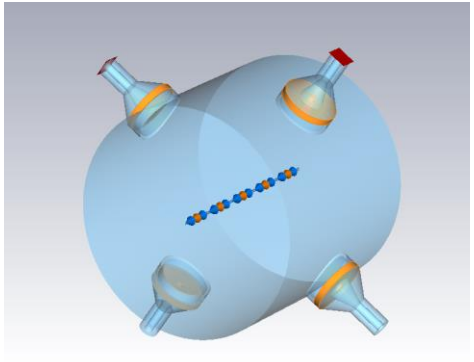
EEFACT 2022
13 SEP 2022
JACQUELINE KEINTZEL
FCC-EE LATTICE DESIGN
20

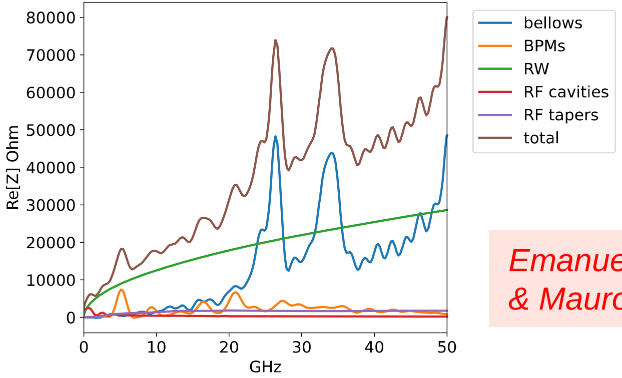
BPM Requirements (3)

- **Please distinguish BPM requirements for**
  - ***Standard luminosity operation***
    - Serving orbit corrections, OFB, lumi tuning, polarization tuning
  - ***Beam commissioning, optics measurements, MDs, etc.***
    - Exotic beam formats, pilot bunches, etc.

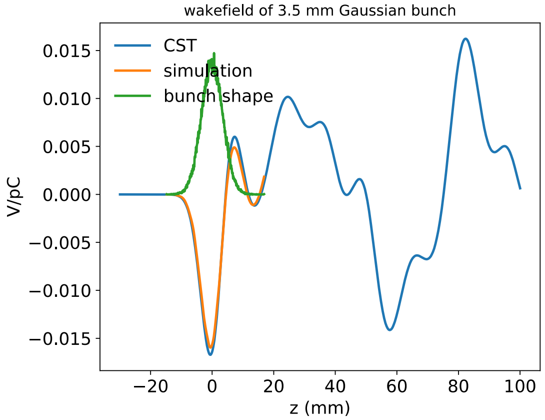
- **BPM resolution: <1 µm (orbit mode), <10 µm (BxB / TxT mode)**
  - ***However, in a very large beam pipe 70 mm dia. (FCC-ee arcs)***
- **BPM alignment & accuracy: 1-10 µm**
  - ***Arc BPM location at the quads? (or sextupoles?!) Movers? Pre-alignment accuracy?***
  - ***Stretched-wire BPM-quad electromagnetic pre-alignment?***
- **BPM roll errors: 10-30 µrad, BPM calibration errors: ~1 %**
- **Long term stability & drifts?**
- **Need to draft a BPM requirements document!**

BPM Pickup R&D Activities: Wakefields





Emanuela & Mauro

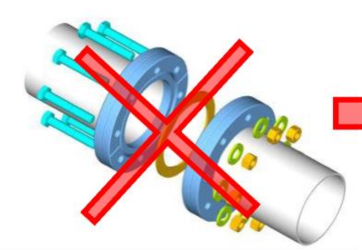


- **Preliminary study by *Emanuela Carideo* and *Mauro Migliorati***
  - ***Simplified button style BPM pickups, pipe with and w/o winglets***
  - $k_{loss} \approx \frac{10mV}{pC}$ ***@ 3.5mm RMS bunch length***
  - $Z_{\parallel}$ ***within the regime of other components and resistive wall***
- **More detailed studies are planned in frame of BPM pickup R&D**
  - ***Including beam studies and lab measurement characterization***

BPM Pickup R&D Activities: Integration

Cedric

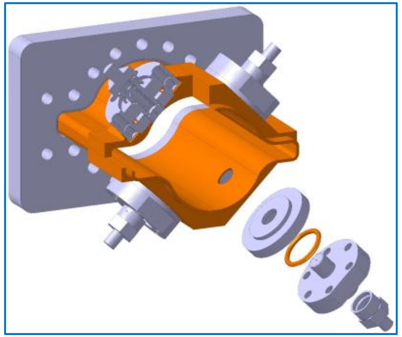
Current system

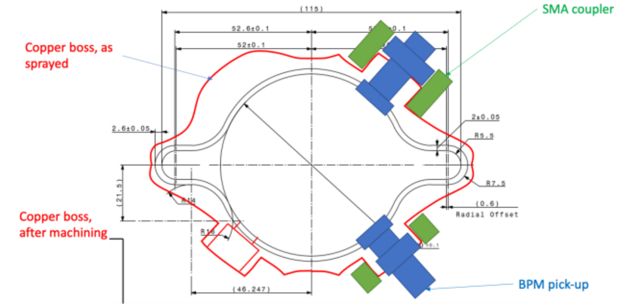


Typical ConFlat flange

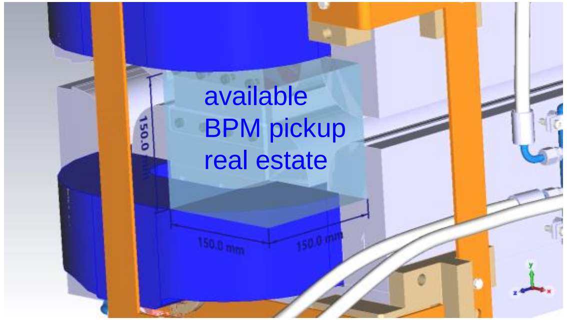
New concept

Proof of concept of SMA connectors for Ultra High Vacuum (UHV) chambers.

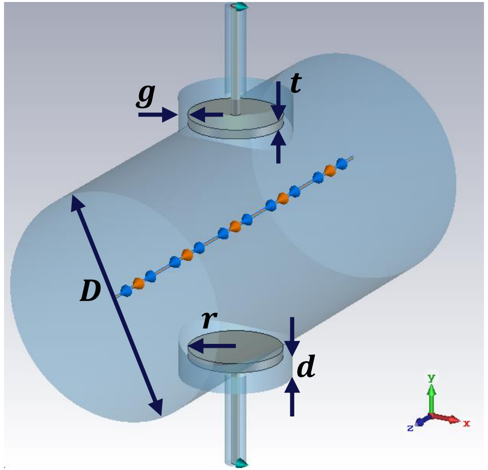


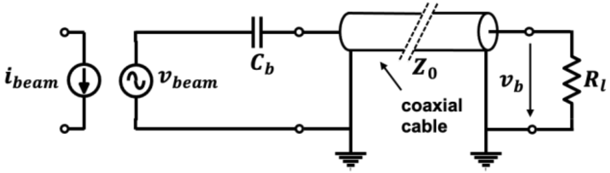


- **CERN vacuum team (*Cerdic Garion*) R&D on additive manufacturing**
  - ***Cost effective method to integrate the UHV BPM button feedthroughs into the vacuum chamber***
  - ***Requires more communication and studies***
    - Feedthrough RF properties, button size and mechanical details, pickup position non-linearities, EM alignment with quad, maintenance, etc.
- **Real estate at the quad**
  - ***Preliminary study hints no "extra" space is required for the BPM pickup***

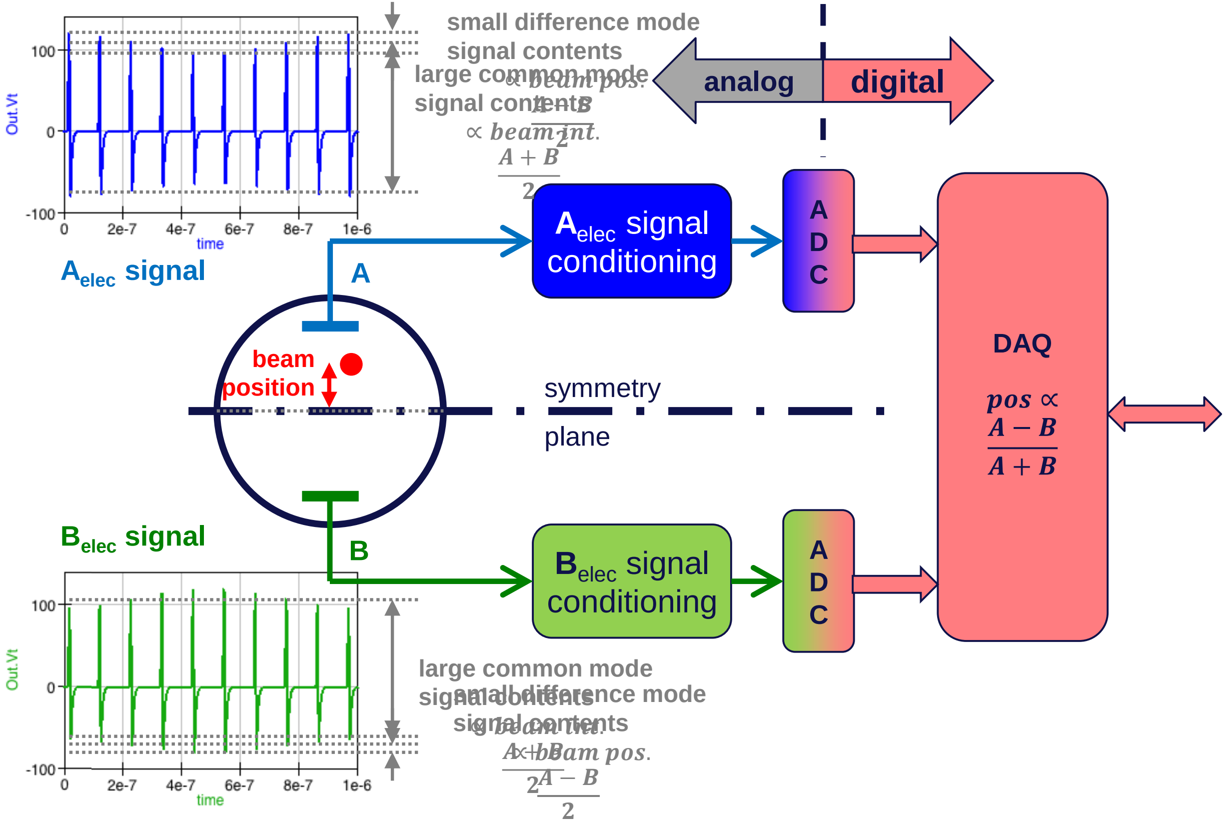


BPM Operational Principle



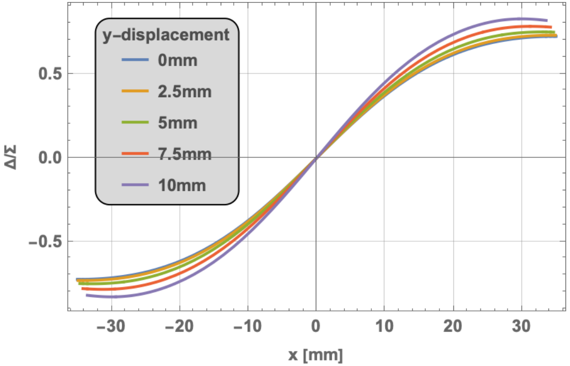


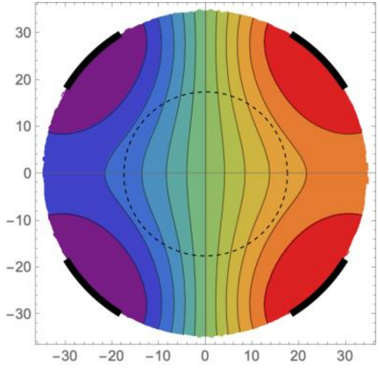
$$Z_b(\omega) = \frac{V_b(\omega)}{I_{beam}(\omega)} = \phi R_l \frac{\omega_1}{\omega_2} \frac{j\omega/\omega_1}{1 + j\omega/\omega_2}$$

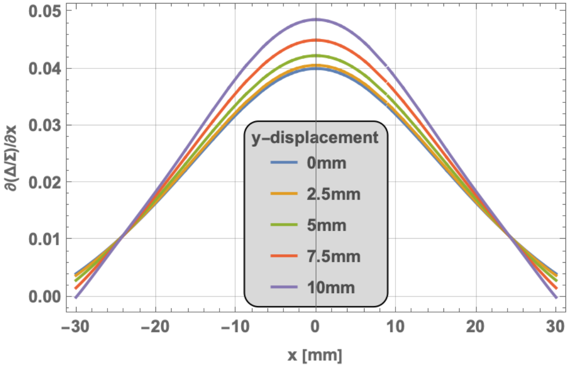


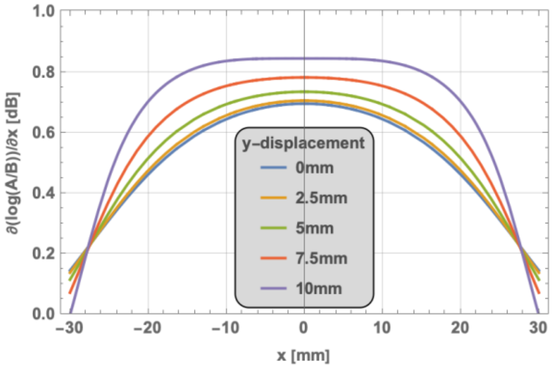
Button-Style BPM Position Characteristics

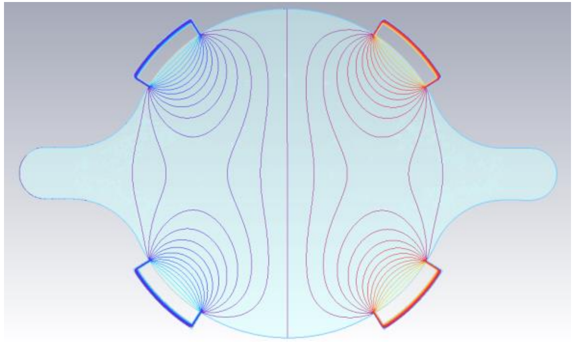
- **Analytical and simplified numerical analysis**



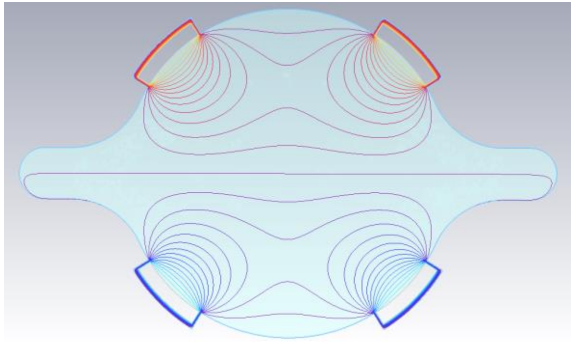








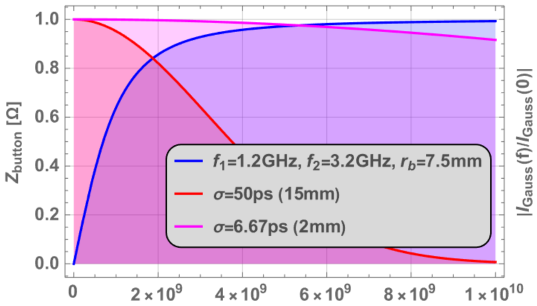
BPM position behaviour: horizontal

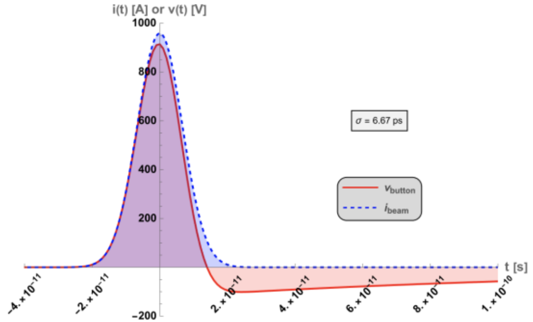


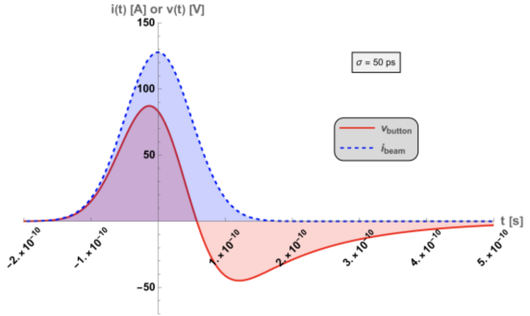
BPM position behaviour: vertical

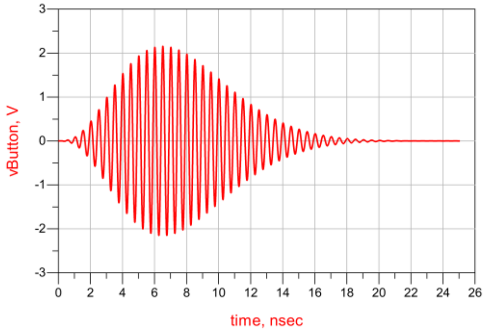
Button BPM Signal Characteristics

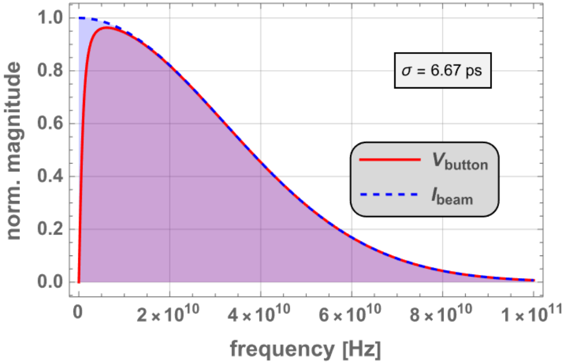
- **Single bunch response (idealized!)**
  - $n = 1 \cdot 10^{11}, \sigma = 6.67\ ps$ *(2 mm) and 50 ps (15 mm)*
  - *Band-pass filter:* $f_c = 2\ GHz, BW = 80\ MHz$

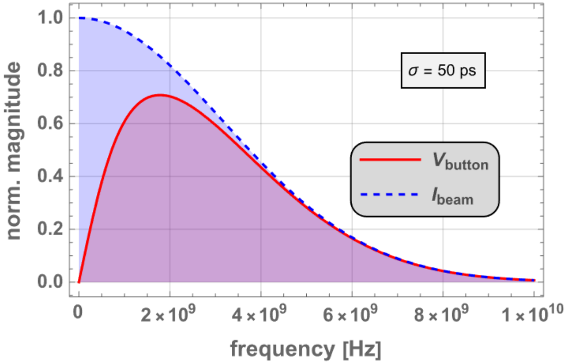












BPM Resolution Limit

- **Ideal conditions: Button BPM and Gaussian band-pass filter**
  - ***Consider only the linear term of the position characteristic***

$$\text{pos.} = k_{BPM}\frac{\Delta_{meas}}{\Sigma_{meas}} = k_{BPM}\frac{\Delta_{BPM}+\Delta_{noise}}{\Sigma_{BPM}+\Sigma_{noise}} \cong k_{BPM}\frac{\Delta_{BPM}}{\Sigma_{BPM}} + k_{BPM}\frac{\Delta_{noise}}{\Sigma_{BPM}}$$

$$k_{BPM}\frac{\Delta_{noise}}{\Sigma_{BPM}} = \text{resolution} = k_{BPM}\frac{A_{noise}-B_{noise}}{A_{BPM}+B_{BPM}}$$

  - ***Assuming small beam displacements***

$A_{BPM} \approx B_{BPM} \approx S$

$A_{noise} \approx B_{noise} \approx N$

A_{noise}, B_{noise}: uncorrelated

$$\text{resolution} = k_{BPM}\frac{\sqrt{2}N}{2S} = \frac{k_{BPM}}{\sqrt{2}}\left(\frac{S}{N}\right)^{-1}$$

  - ***FCC-ee BPM values:***

$k_{BPM} = 25\ mm\ \ (0.7\ \ dB/mm)$

$V_{signal} \approx +16\ dBm = 1.4\ V \qquad V_{noise} = \sqrt{4\ k\ T\ R\ \Delta f} \approx 8.14\ \mu V$

$n = 10^{11}$

$\sigma_{bunch} = 2\ mm$ (single bunch)

$k = 1.38 \cdot 10^{-23}\ {}^{J}/_{K}$

$T = 300\ K$

$R = 50\ \Omega$

$\Delta f = 80\ MHz$ (Gaussian BPF)

$$\Rightarrow \frac{S}{N} \approx 1.72 \cdot 10^{5}\ (105\ dB)$$

$\Rightarrow$ theoretical resolution limit $\approx 0.1\ \mu m$ (single bunch)

Some notes on the BPM resolution

- **The resolution limit cannot be achieved in practice!**
  - ***The analysis is purely based on uncorrelated thermal noise***
  - ***A variety of effects will degrade the achievable resolution!***
    - Signal losses in cables and passive electronic components, noise of the pre-amplifier, quantization noise of the ADC, etc.
    - Some adjustments are necessary on the high-level BPM pickup signals
      - *Typical ADC FSR requires attenuation!*

- **The turn-by turn and orbit resolution < single bunch resolution**
  - ***Scales with $\sqrt{n_b}$, with n_b being # of bunches per turn for TxT resolution***
    - For $n_b = 1$ the BxB and TxT resolution is identically
    - For $n_b = 10000$ the TxT resolution is 100x better than the BxB resolution!
  - ***Scales with $\sqrt{n_t}$ for the # of turns for the orbit measurement***
    - Equivalent to the effective bandwidth BW in V_{noise}

Mechanical Tolerances and BPM Offset

- **Determine the BPM accuracy!**
- **Systematic study and analysis by IHEP for the HEPS**
  - ***Publication still under review!***
  - ***Analytical and numerical analysis, plus measurements on a production series.***
  - ***Optimum button diameter / capacitance***
    - Insensitive to mechanical tolerances
  - ***Analysis of trapped modes and the related button heating***

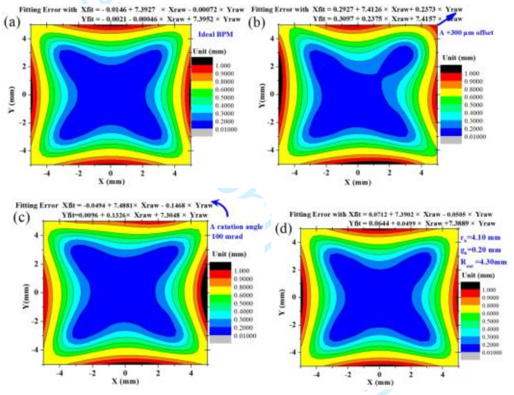


Fig. 7 Fitting error, A_0 (offset), A_1 (position sensitivity coefficient) and A_2 (x–y coupling coefficient). **a** An ideal BPM. **b** Button A with 300 μm offset. **c** Button A with 100 mrad angle error; location azimuthal angle θ was 50.7° instead of 45°. **d** Radius and gap of Button A were 4.1 and 0.2 mm, respectively

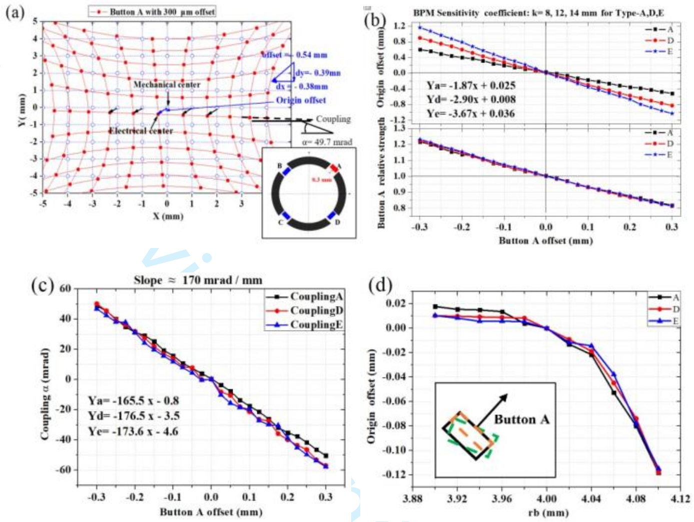
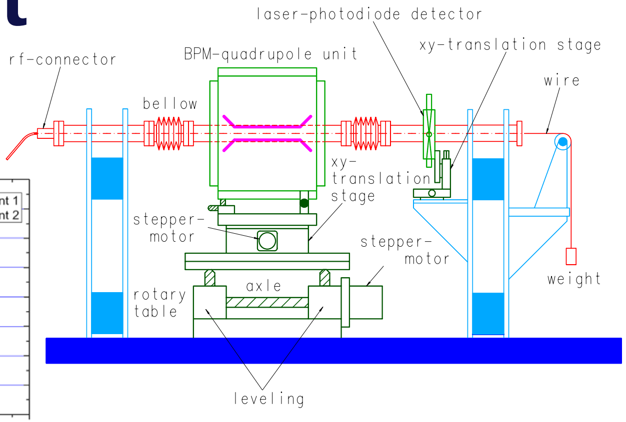


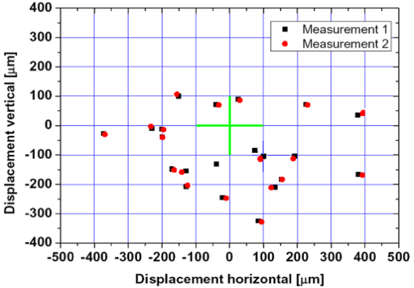
Fig. 6 **a** Mapping results for button A with 0.3 mm retracted, $x = k \times X_{raw}$, $y = k \times Y_{raw}$, $A_0 = A_2 = B_0 = B_1 = 0$, $k = A_1 = B_2 = 8$ mm. **b** Electro–mechanical offset and signal strength caused by button offset. $k = A_1 = B_2 = 8$, 12, 14 mm for three types of BPM as an approximation of 7.8, 11.3, and 14.1 mm, respectively. **c** Coupling caused by button offset. **d** Electro–mechanical offset Vs r_b

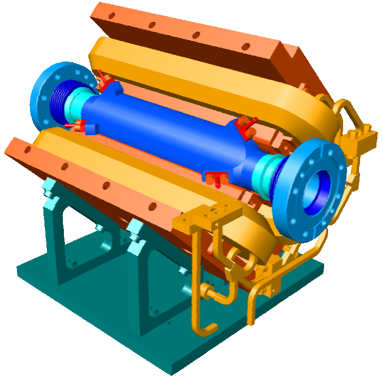
Electromagnetic Pre-Alignment

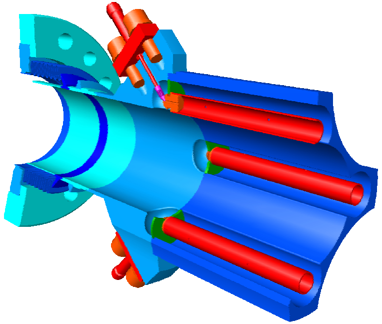
- **Between quadrupole and BPM pickup**
  - ***Stretched-wire based at FLASH (DESY)***
    - For a stripline BPM pickup
  - ***BPM-quad offset reproducibility ~10 µm***

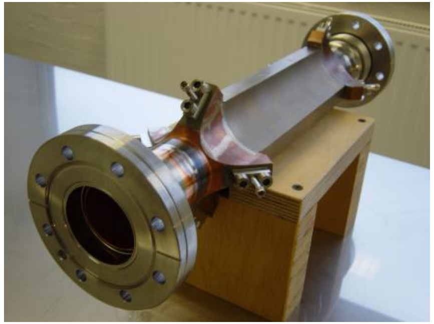
- **PACMAN project at CERN**
  - ***Demonstrated EM pre-alignment between quadrupole and BPM pickup of a few µm***
    - Utilizing a 15 GHz CLIC/CTF cavity BPM

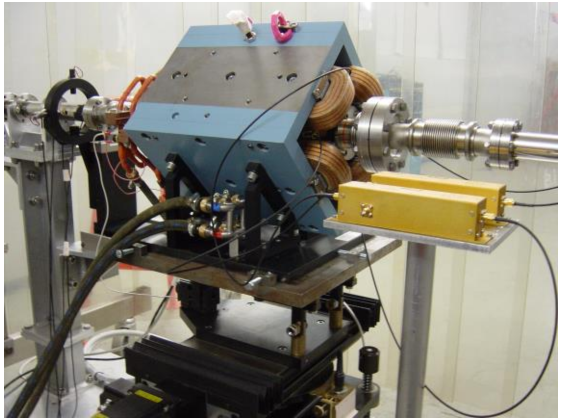












Next Steps…

- **FCC-ee Beam Instrumentation Mini-Workshop**
  - ***21st and 22nd November 2022 at CERN Meyrin***
  - ***Will cover all FCC-ee beam instrumentation R&D, including BPMs***
- **FCC-ee BPM Brainstorming**
  - ***Kickoff meeting in Spring 2023***
  - ***Need to draft a BPM requirements document***
  - ***Need to converge the various R&D activities wrt. FCC-ee BPMs***
- **Doctoral Student on FCC-ee BPM button pickup**
  - ***In collaboration with the Oxford University (Phil Burrows)***
  - ***Starts in April 2023 at CERN***
- **CERN staff position for BPM R&D**
  - ***Starts in 2023***
  - ***Includes FCC-ee BPM R&D (among other activities)***

Discussion

- **The required BPM precision (resolution) and accuracy cannot be defined by the BI team!**
- **An FCC-ee BPM requirements document is due!**
    - ***Should cover arc and IR BPMs***
- **FCC-ee BPM R&D is focused on the BPM pickup**
    - ***Too early to investigate read-out electronics details***
        - Wait for the technology updates in the next 20-25 years
        - BUT: Follow on rad-tolerant and low-latency signal processing & DAQ hardware!
- **BPM R&D needs to be funded!**
    - ***Don't expect to get the performance, what you don't pay for!***
        - Include lab equipment and tools in your budget!
    - ***ESRF upgrade lesson: 5% of the total project budget for BI***
        - ESRF BPMs achieved ~100 nm TxT resolution, ~1 nm orbit resolution!
            - *However, in a much smaller beam pipe aperture!*

Thank you for your attention.