Measuring the beam position at the Cornell Electron Storage Ring

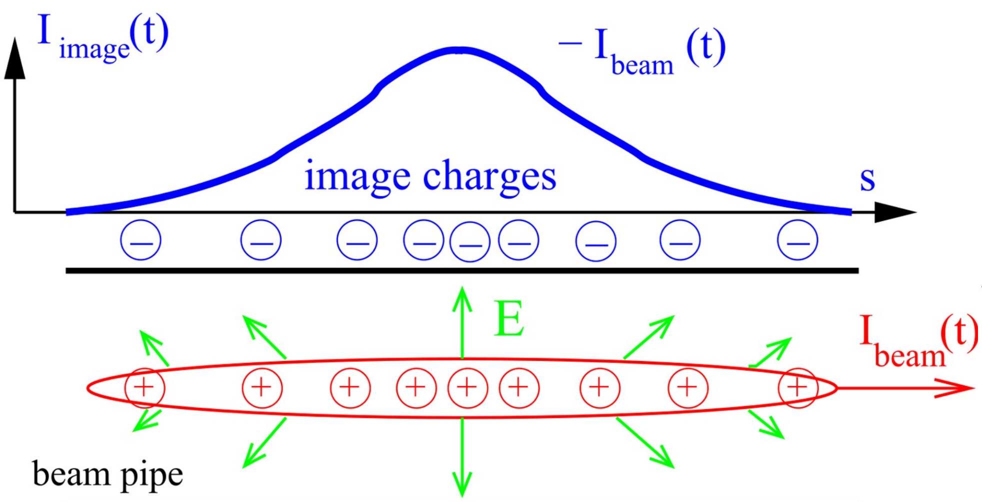
Antoine for the CBPM group

Accelerator Physics JC: March 16, 2023

Introduction

Beam Position Monitor (BPM)

Beam position is the heartbeat of particle accelerators: its measurement is non-destructive and rely on picking-up beam's image charges (currents)



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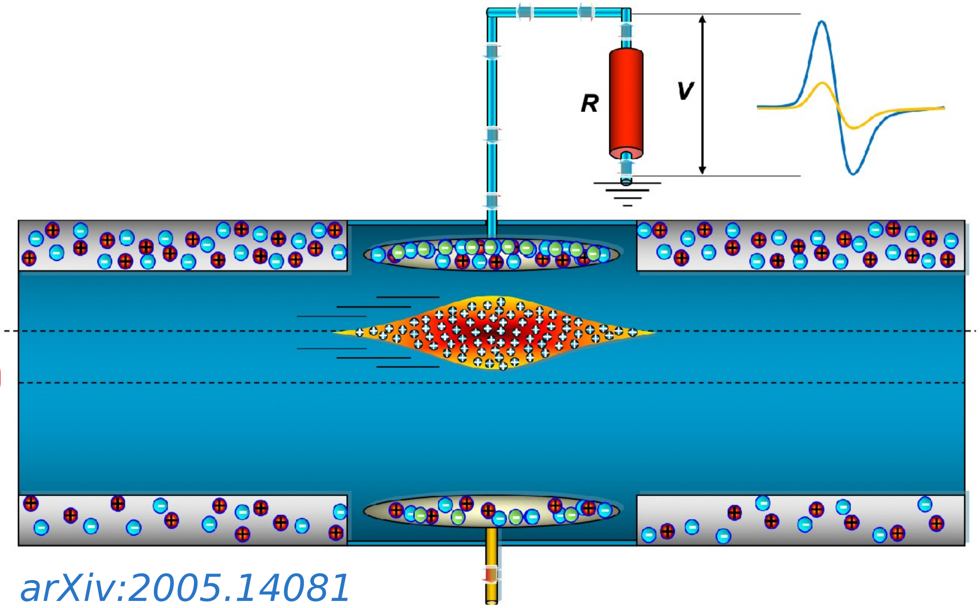


arXiv:2005.14081

Coin-shaped capacitive pick-up electrodes (aka "buttons") generate waveform signal for each passing charged bunch → digitized by readout electronics

BPM system = **pick-up electrodes** + **readout electronics**

Signal intensity difference between symmetrically placed electrodes allows reconstructing beam position

Cornell Electron Storage Ring (CESR)

Currently, CESR is a 6 GeV positron storage ring operating as a bright X-ray source (1 to 200 keV energies) for the Cornell High Energy Synchrotron Source

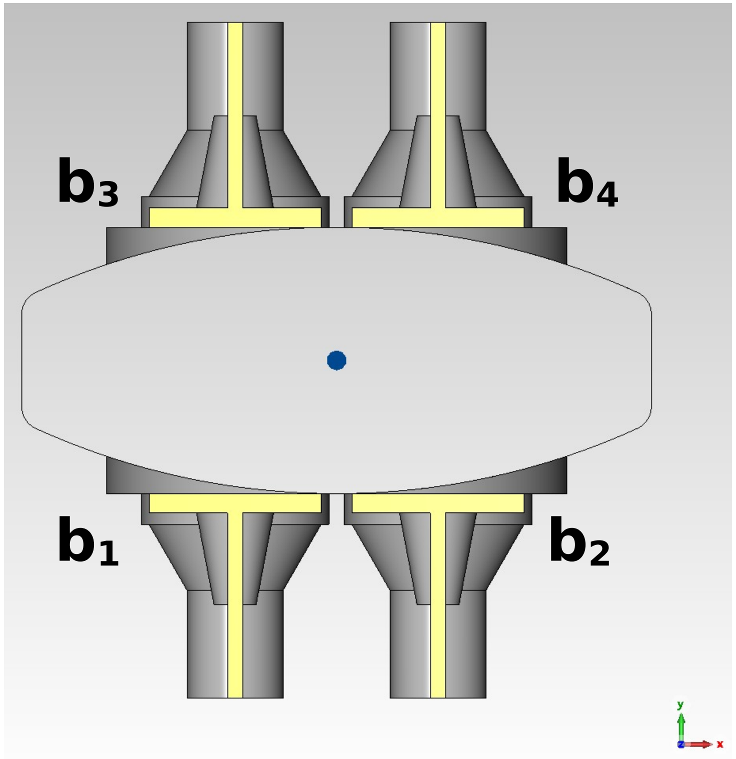
Some CESR facts:

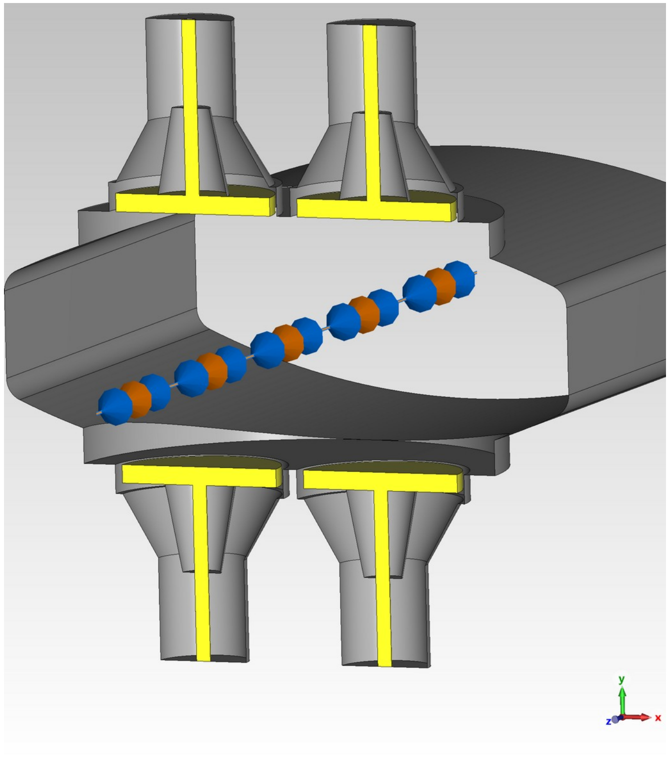
- ✗ 768 meter circumference
- ✗ revolution period of 2.56 µs
- ✗ total operating current of 100 mA
- ✗ beam lifetime of about 17 hours
- ✗ 9 trains of 5 bunches for a total of 45 bunches
- ✗ bunch length of about 100 ps
- ✗ bunch spacing of 14 ns

CESR Beam Position Monitor (CBPM)

Measure beam position at about 100 locations along the 768 meter storage ring

"north arc" BPM geometry modeled in CST microwave studio





Beam position (e.g. horizontal) can be reconstructed linearly via:

$$x = k_x \frac{(b_2 + b_4) - (b_1 + b_3)}{b_1 + b_2 + b_3 + b_4}$$

where k_x is a factor accounting for the vacuum chamber geometry

CESR folks currently involved with CBPM

Grouped by interest in a loose and simplified fashion

Hardware, Firmware

John Barley Len Hirshman Jonathan McDonald,
Bob Meller Will Schlansker Charlie Strohman

DAQ/Operations/Analysis

Antoine Chapelain Mike Forster Laurel Ying

Beam dynamics

Jim Crittenden Vardan Khachatryan
Jim Shanks Suntao Wang

A bit of CBPM history

CBPM-I was in used early 2000s during CESR’s particle physics day with the CLEO[1] experiment that completed in 2008

CESR transitioned in 2008 to its Test Accelerator program (CesrTA) studying low emittance beam and electron cloud effect for the ILC damping rings

CesrTA required new/more elaborate system, **CBPM-2**, that enabled measuring:

- ✗ simultaneously both positron and counter-rotating electron beams
- ✗ orbit within seconds
- ✗ phase within a minute
- ✗ turn-by-turn beam position
- ✗ any and all stored bunch

[1] *Cleopatra and Caesar*

CBPM-2

CBPM-2:

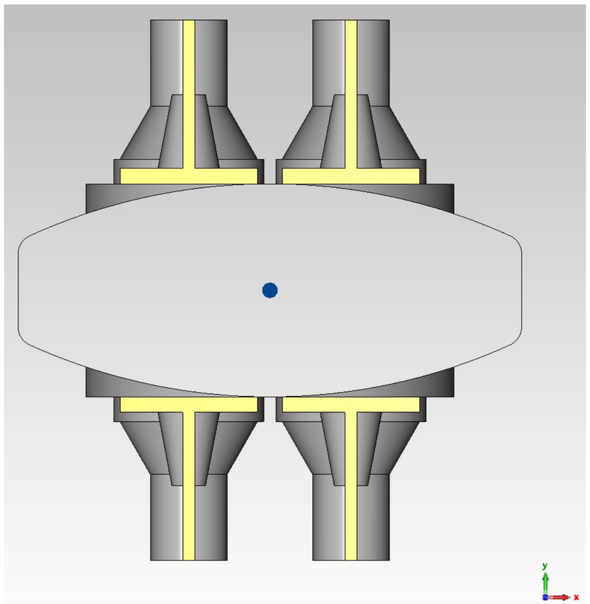
- ✗ R&D started in 2008 leaning on CBPM-1
- ✗ deployment started in 2009 replacing CBPM-1 modules
- ✗ deployment completed in 2010

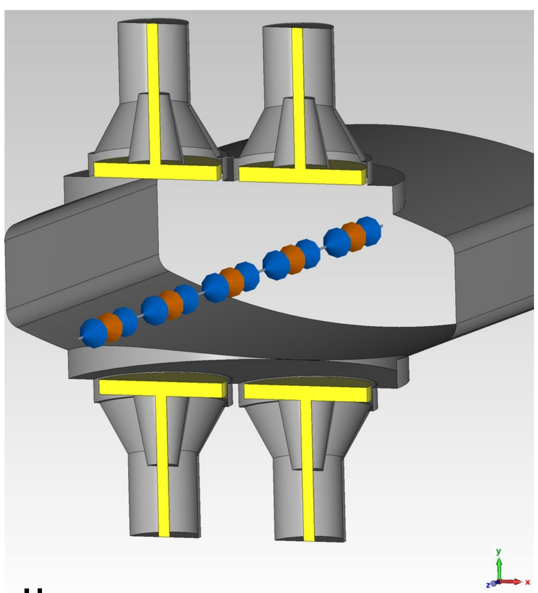
Key features:

- ✗ periodic peak-sampling to handle counter-rotating beam
- ✗ two interleaved 125 MSPS ADCs allow to:
  - ➢ sample contiguous bunches spaced 4 ns part via (same species)
  - ➢ sample both e^+/e^- bunches with 14 ns spacing
- ✗ fixed and variable gain amplifier to accommodate wide range of bunch current

Expected button response to bunch passing by

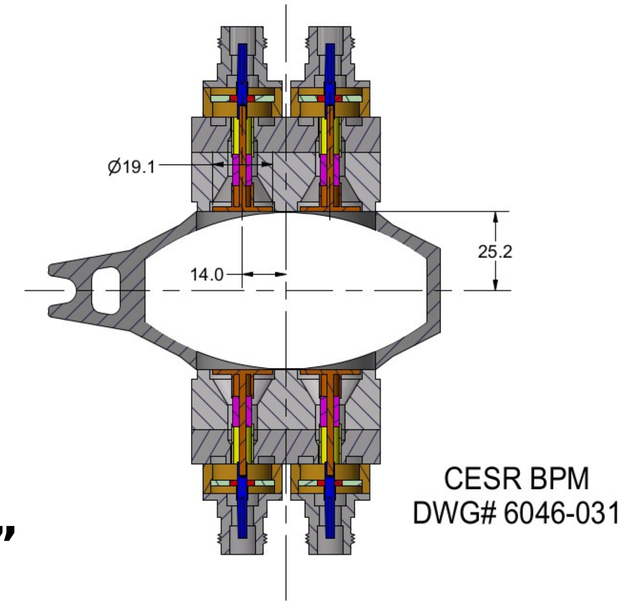
Wakefield simulation in CST Microwave studio using mechanical drawings

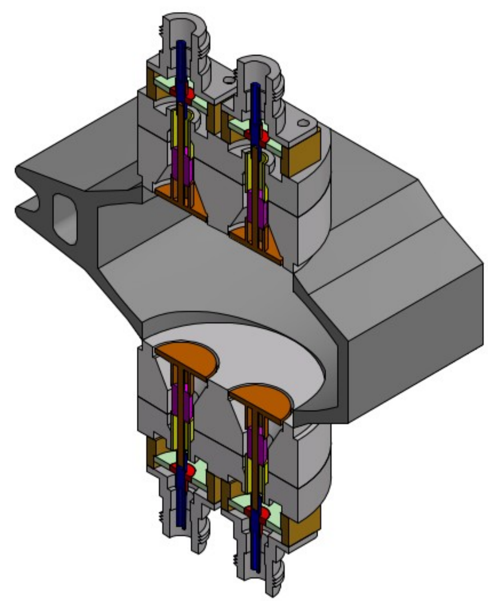




MWS modeling

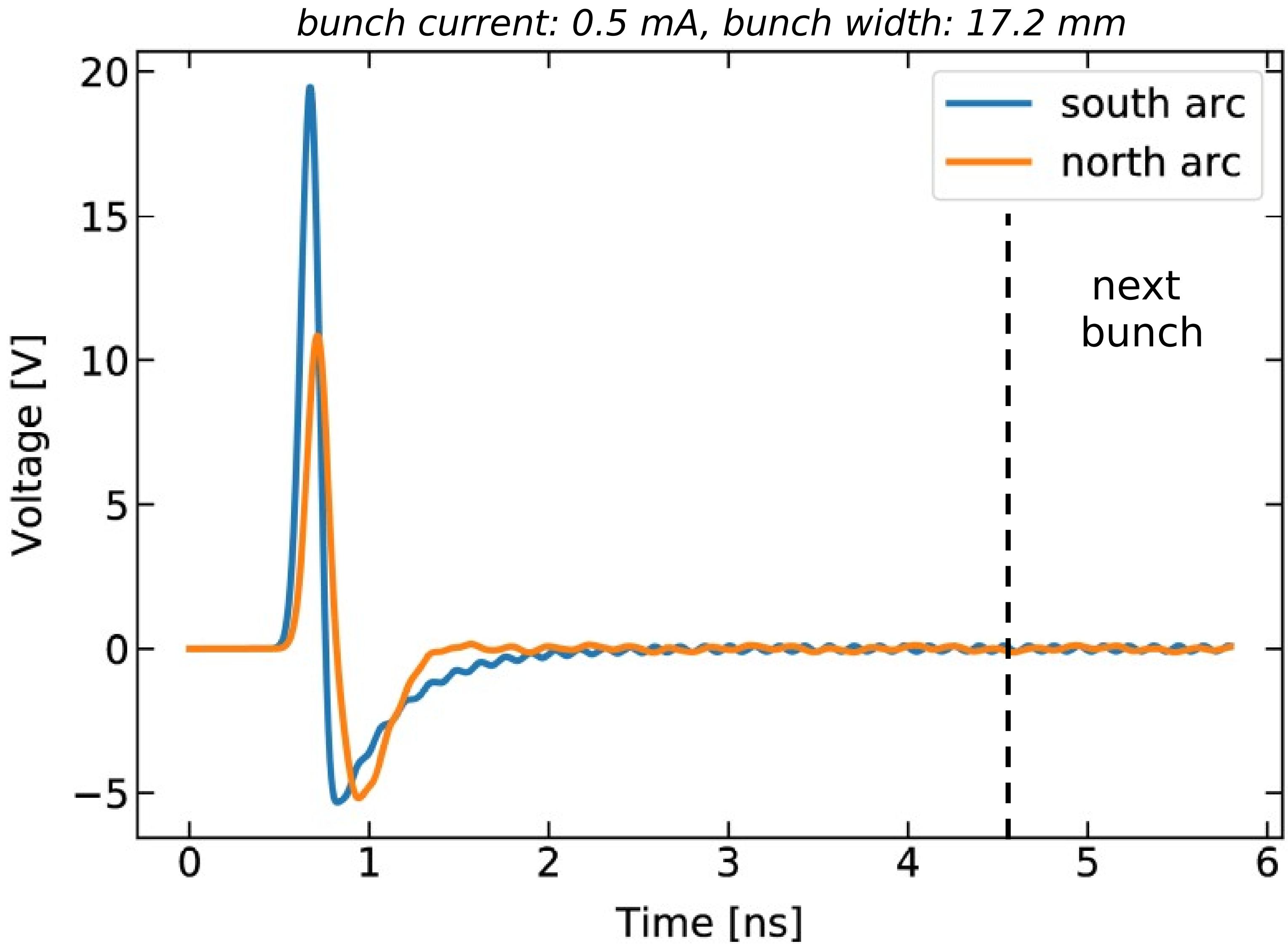
“north arc” vacuum chamber





Drawings

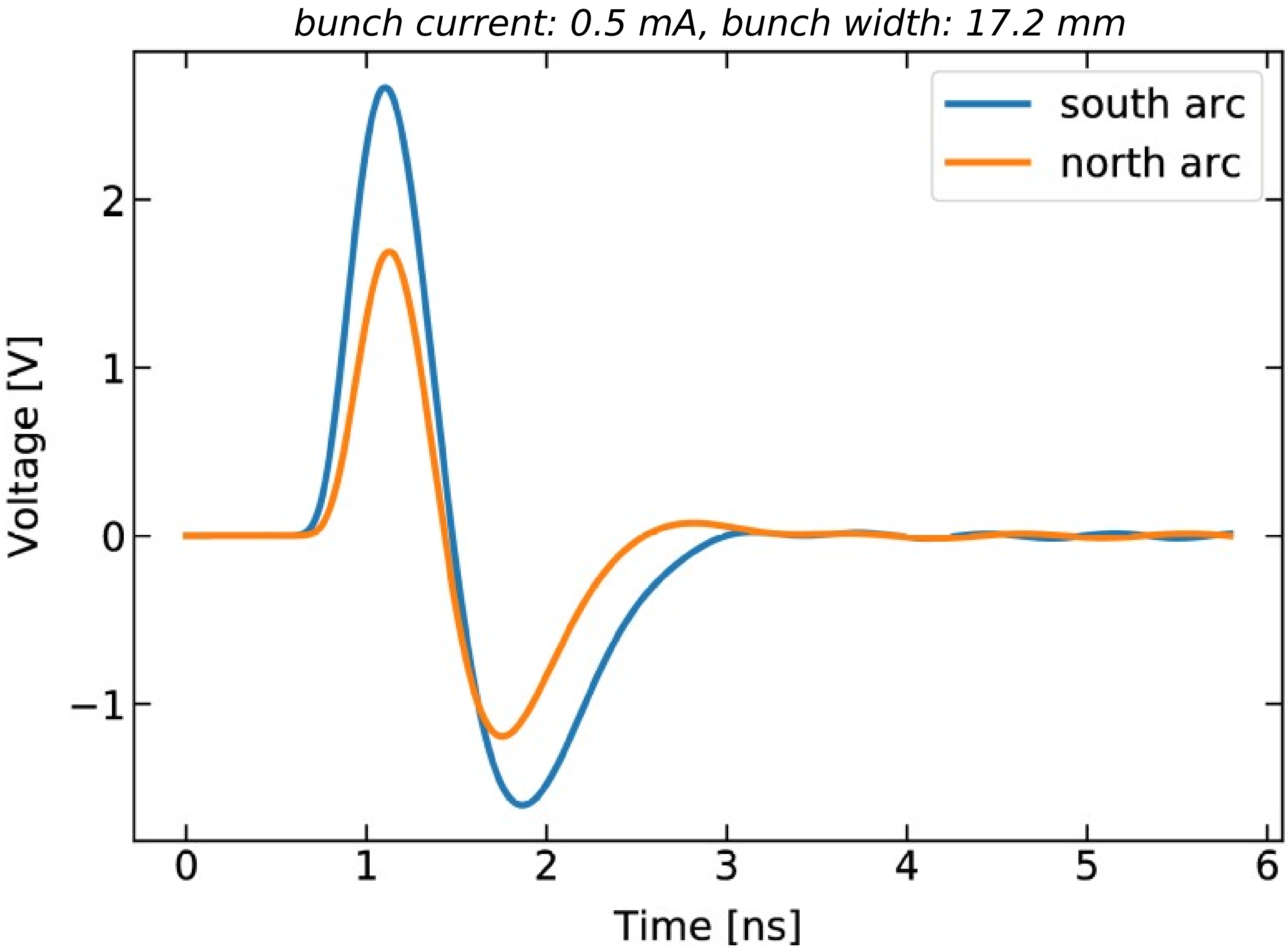
Waveform produced by button (direct response to the bunch)



CST Microwave studio wakefield simulation

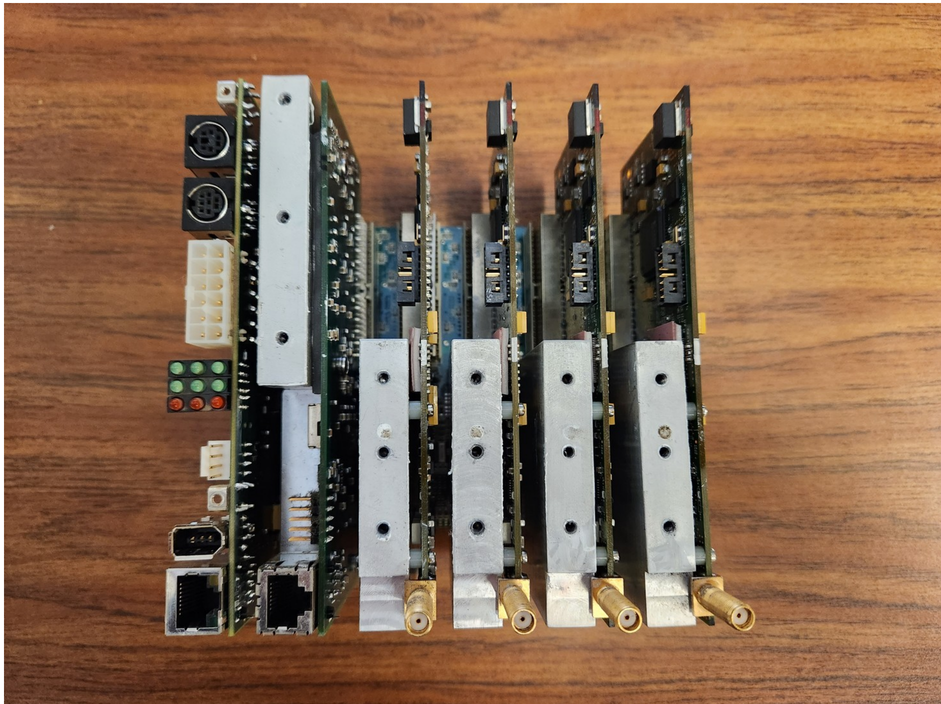
Expected button response to bunch passing by

Waveform digitized by 600 MHz bandwidth ADC

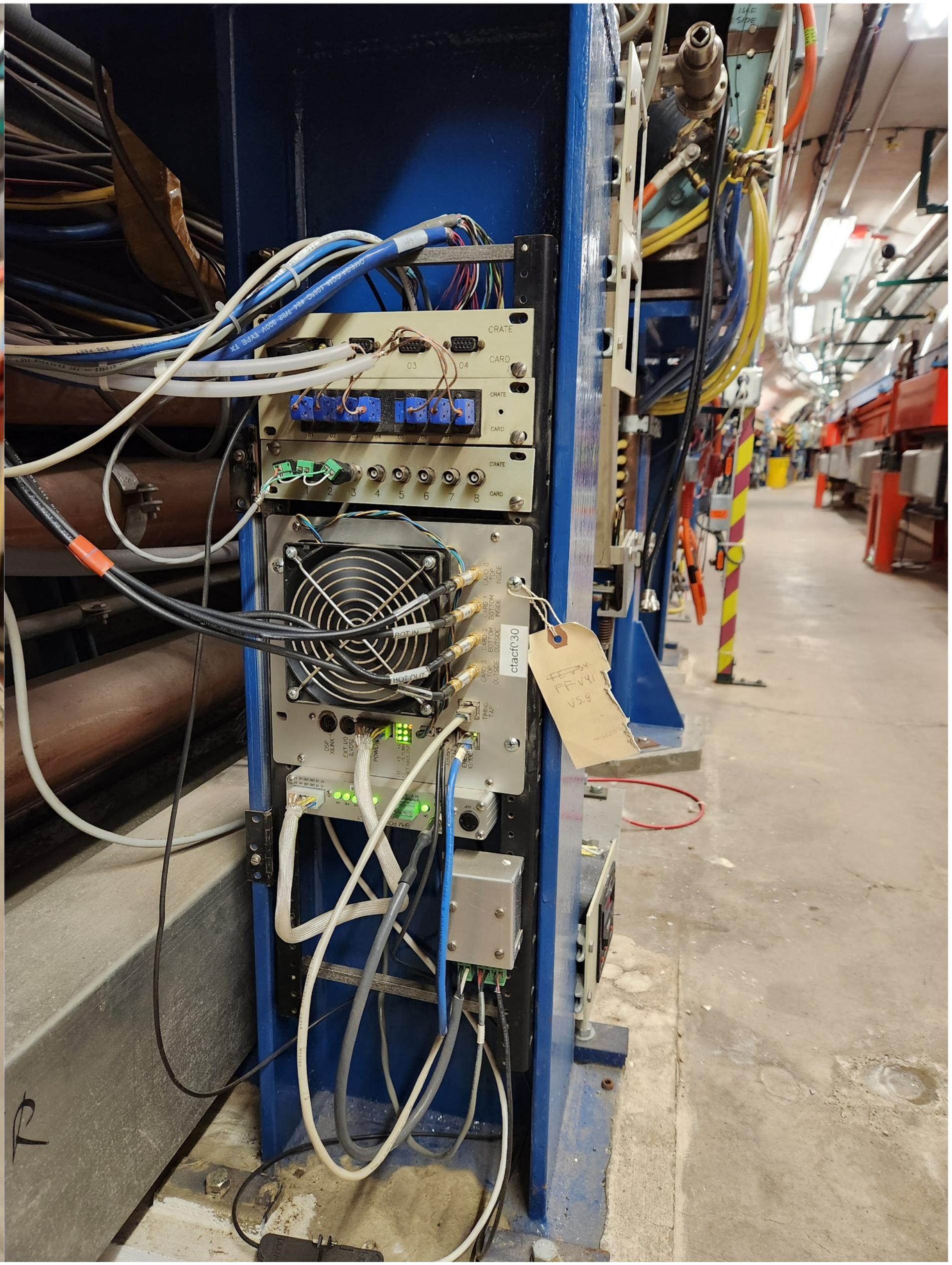


CST Microwave studio wakefield simulation

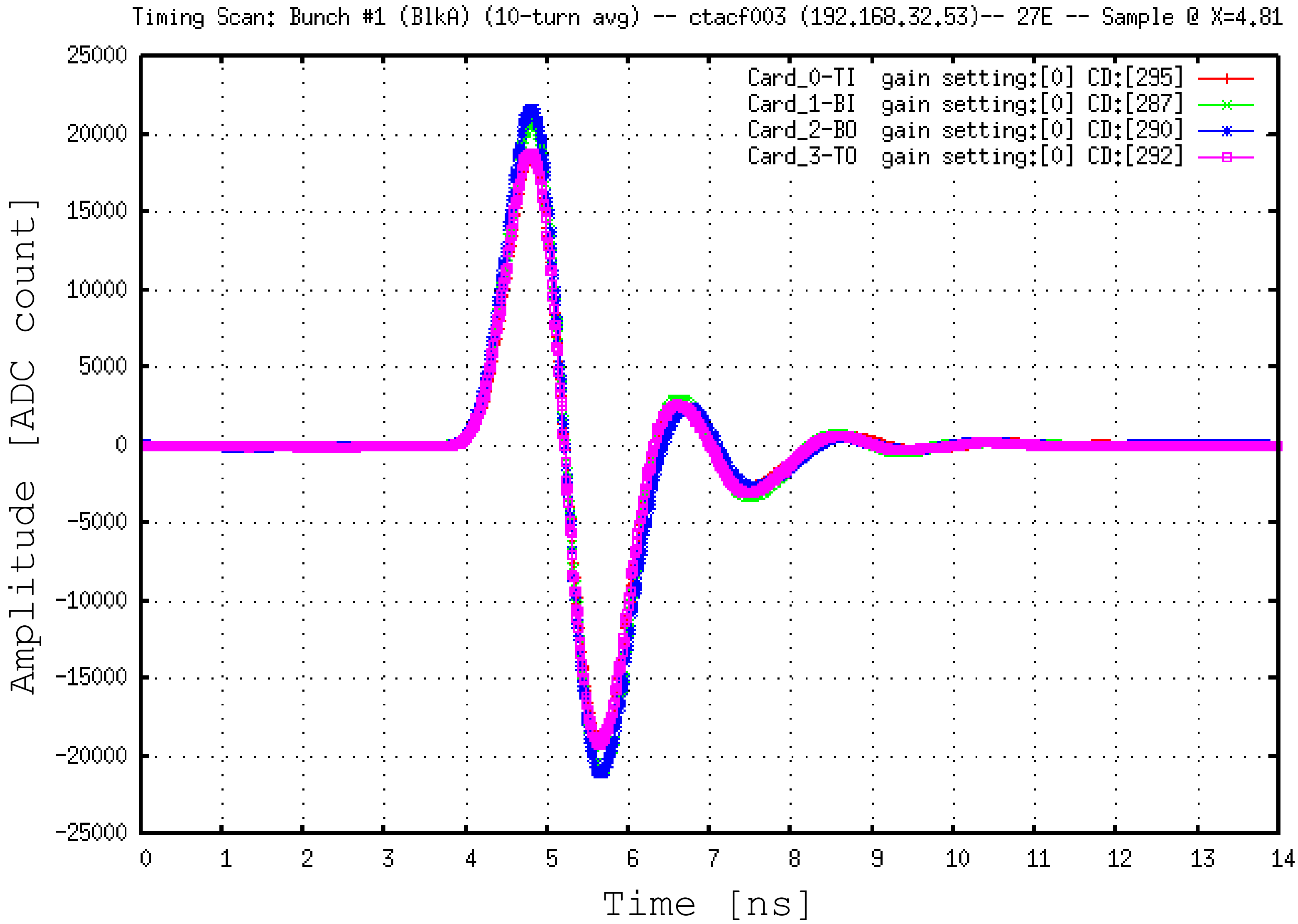
CBPM-2 readout electronics




CRATE
CARD
1 2 3 4 5 6 7 8
BOT IN
BOT OUT
ctacf030
TIMING TAP
DSP XILINX
EXT I/O (LVDS)
FAN
ENET



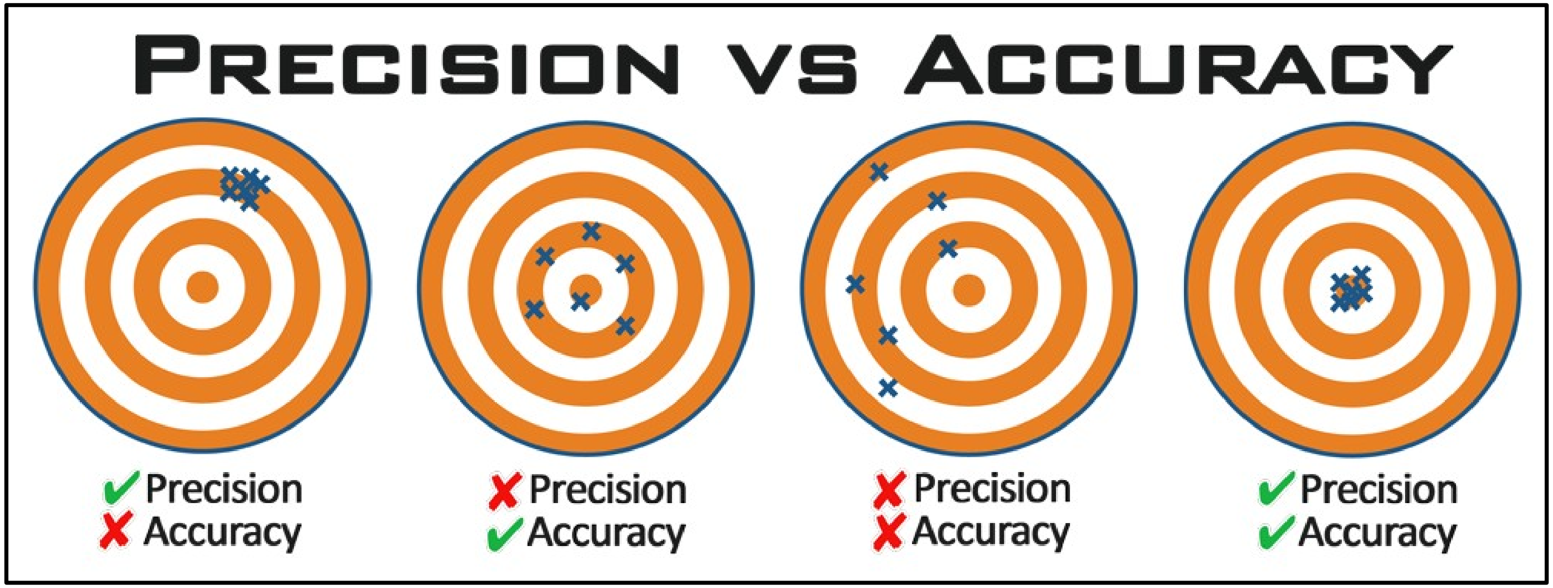
Digitized waveform measured sweeping sampling time in 10 ps steps



Electronics has a lot more going on than what the simulation has...

Precision and accuracy on the beam position measurement

We care most about turn-by-turn beam position **precision,** i.e.: if the beam position were not to change, how **repeatable** is its measurement? We want to know well how orbits compare to each other.

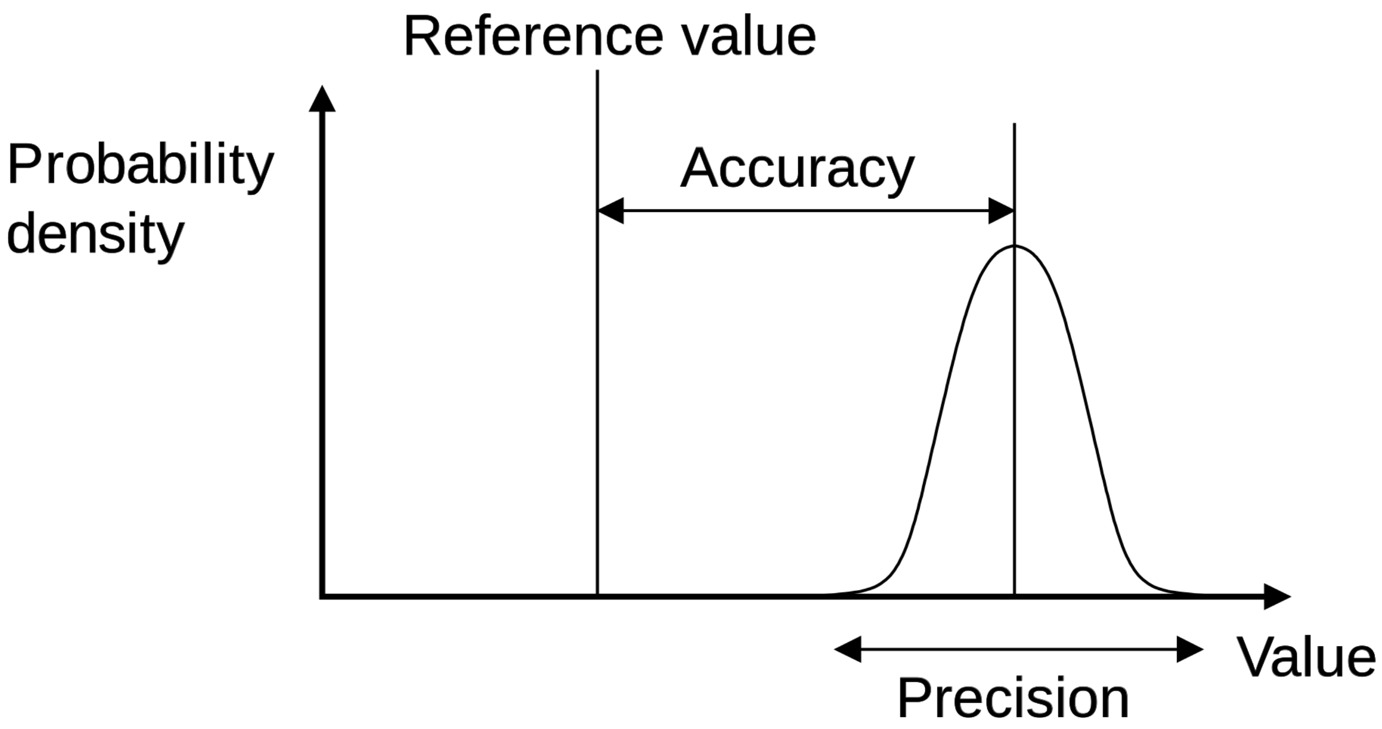


typical at CESR:

precision: $O(10)$ micron
accuracy: $O(100)$ micron

Turn-by-turn beam position precision

We care most about turn-by-turn beam position **precision,** i.e.: if the beam position were not to change, how **repeatable** is its measurement? We want to know well how orbits compare to each other.



precision ≡ **standard deviation** of a set of data points

accuracy ≡ **bias** (offset) of the mean of a set of data points

precision = repeatability

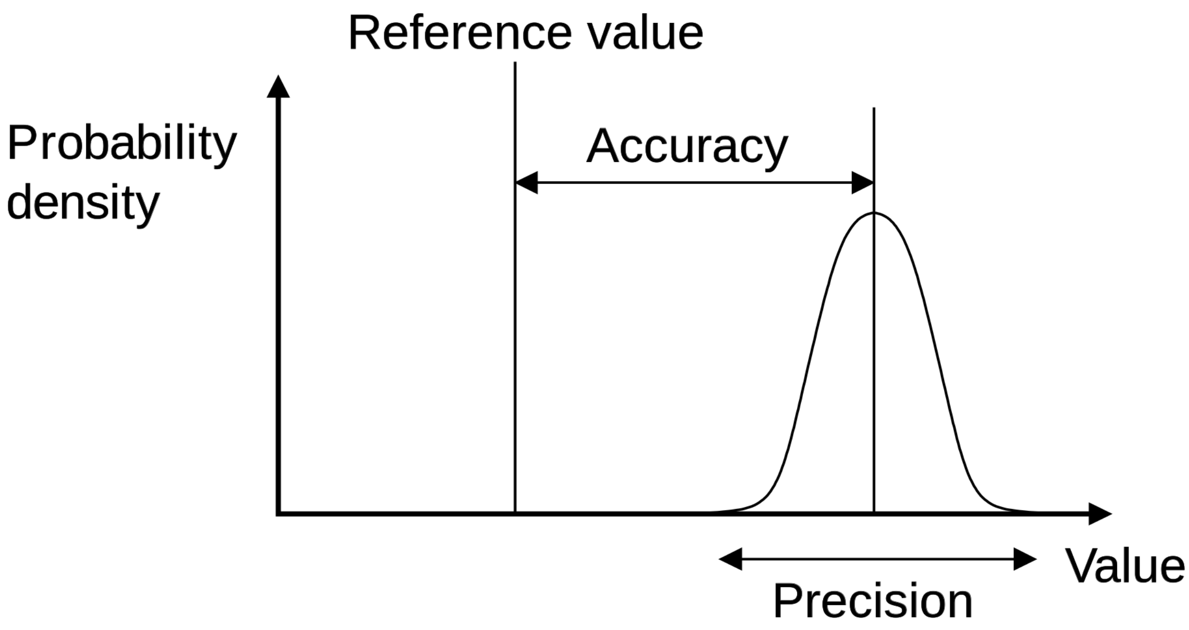
Sources of error:

- ✗ electronics noise
- ✗ sampling clock jitter
- ✗ peak-sampling alignment

accuracy = bias (fixed offset)

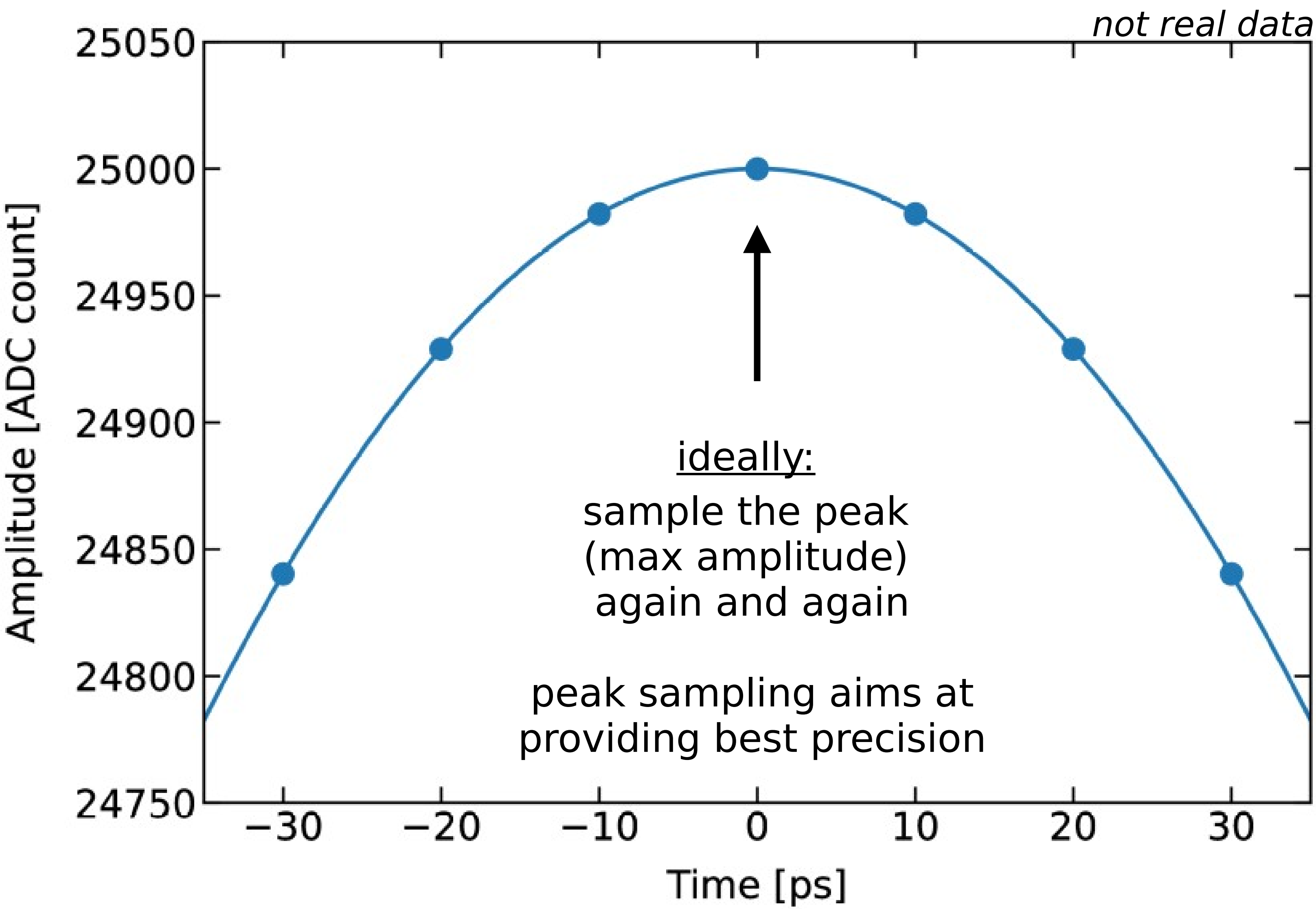
Sources of error:

- ✗ electronics gain
- ✗ button displacement (i.e. depth)
- ✗ button tilt
- ✗ peak-sampling alignment



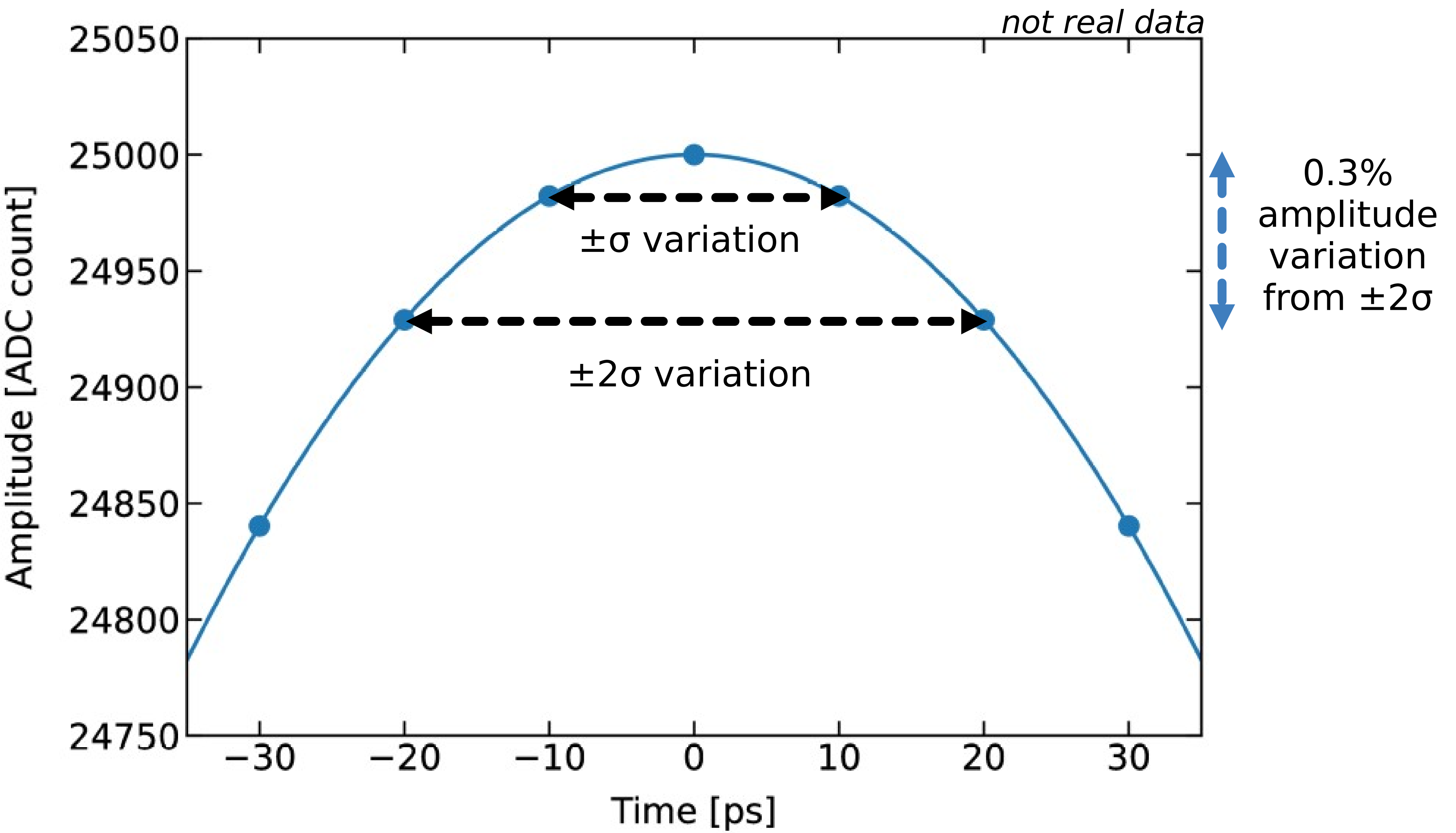
Peak-sampling and precision

Precision is all about measurement-to-measurement variation of the signal amplitude caused by the error sources: sampling point moving about the peak



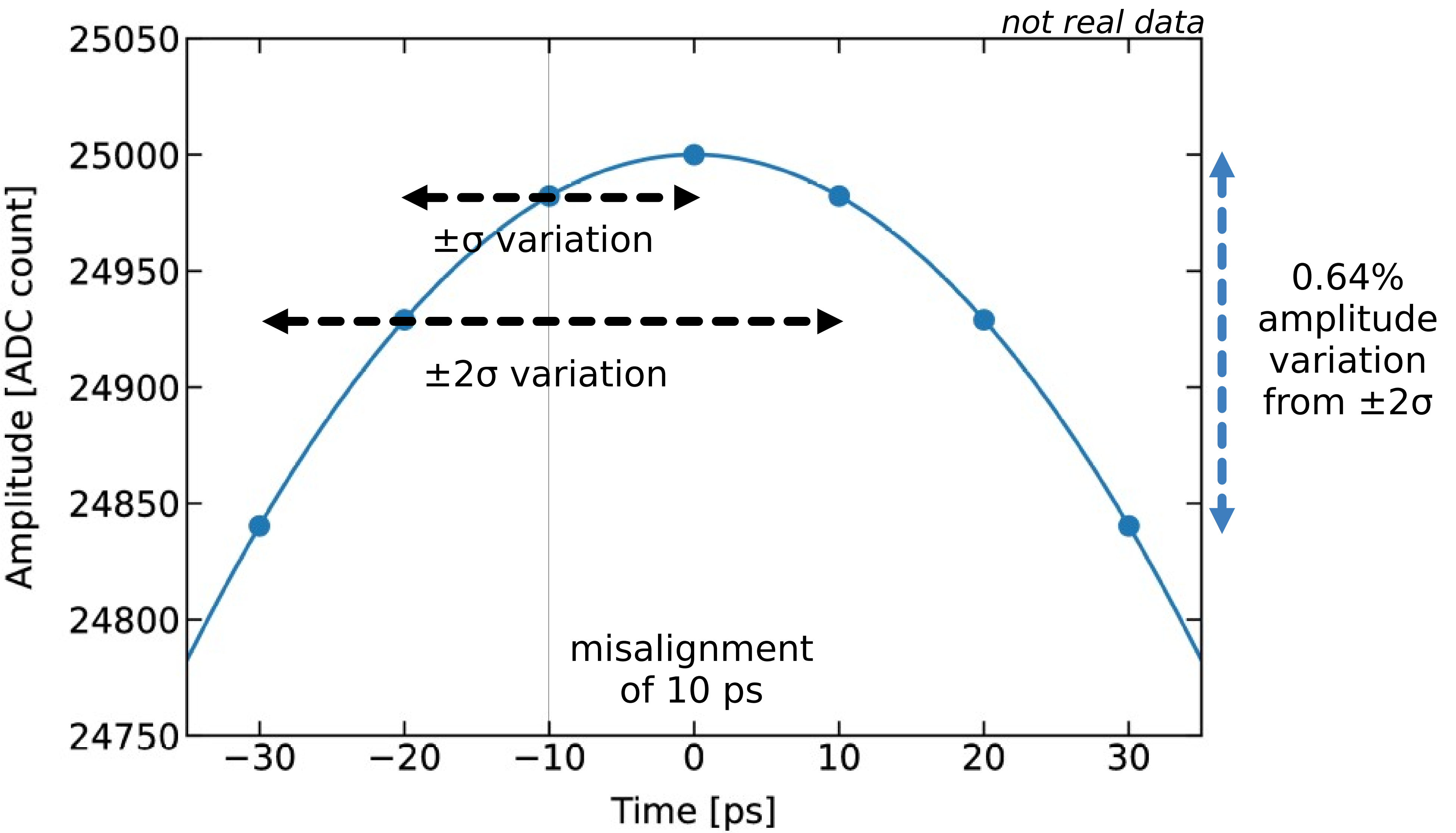
Precision limitation **#1**: sampling clock jitter

Sampling clock jitter randomly follows measurement-to-measurement a normal distribution with a width σ=10 ps

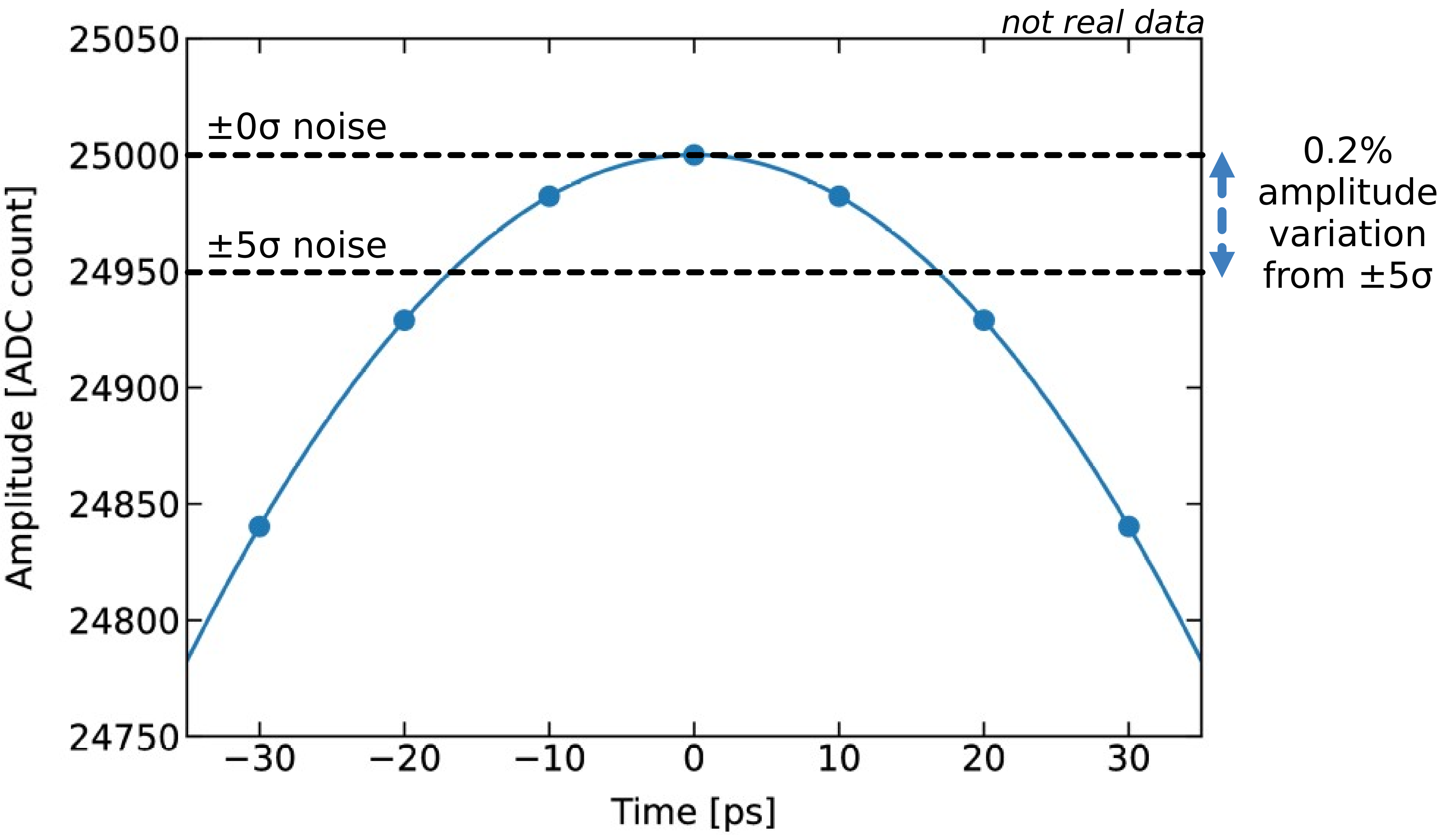


Precision limitation **#2**: peak-sampling alignment

Alignment to the peak is done time sweeping in 10 ps steps → misalignment nonlinearly increases error due to jitter as downward slope gets steeper

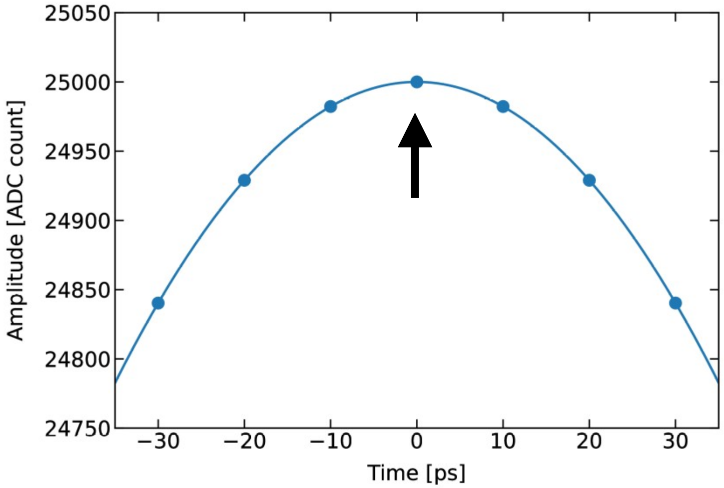


Electronics is noisy: it varies the digitized signal amplitude randomly following a normal distribution with a width σ = 10 ADC counts



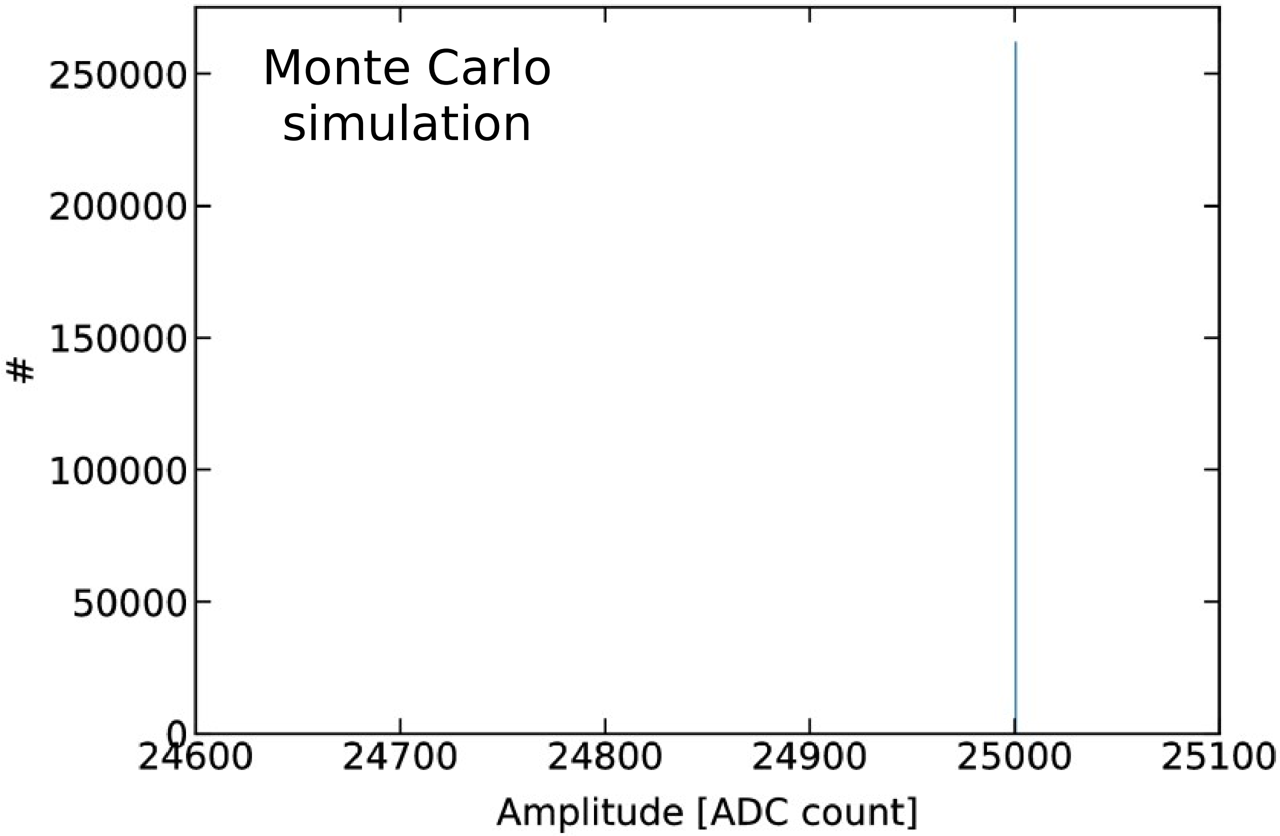
Button amplitude distribution

Reading out button amplitude for many consecutive turns provides us with a distribution that is shaped by error sources. Let's assume a **stationary beam**.



ideal world:

aligned on the peak for every measurement



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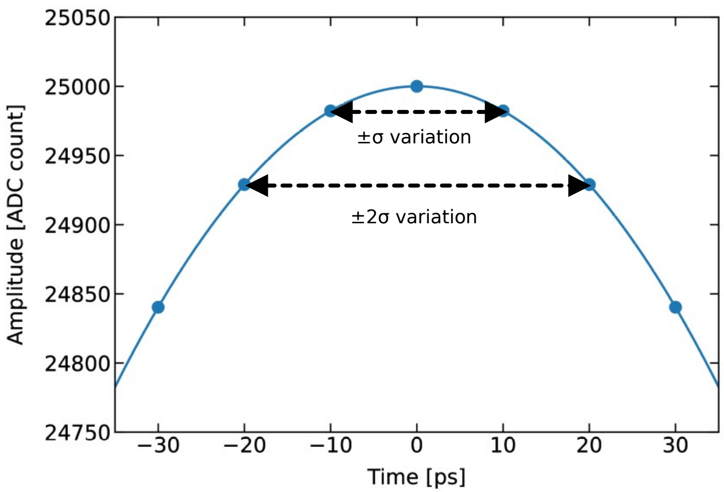
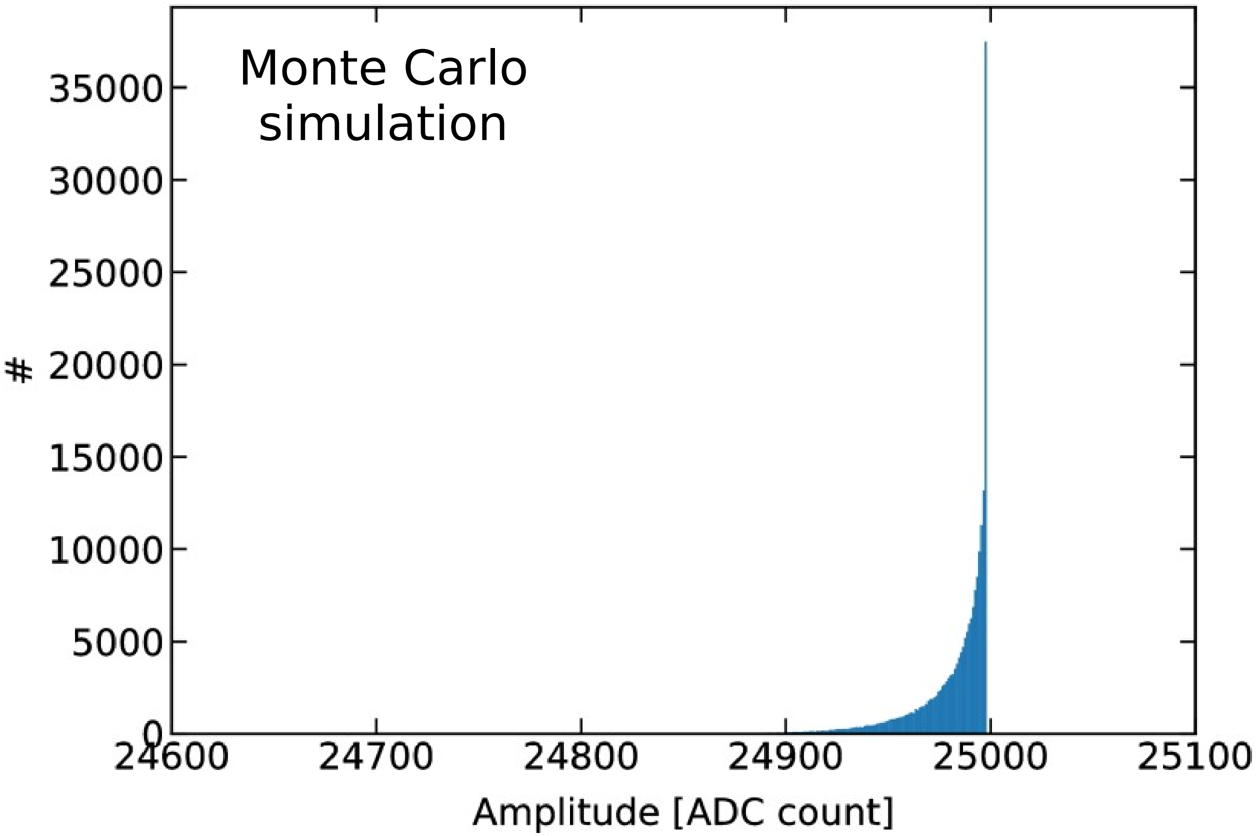


jitter world:

moving about peak randomly following normal distribution with σ=10 ps



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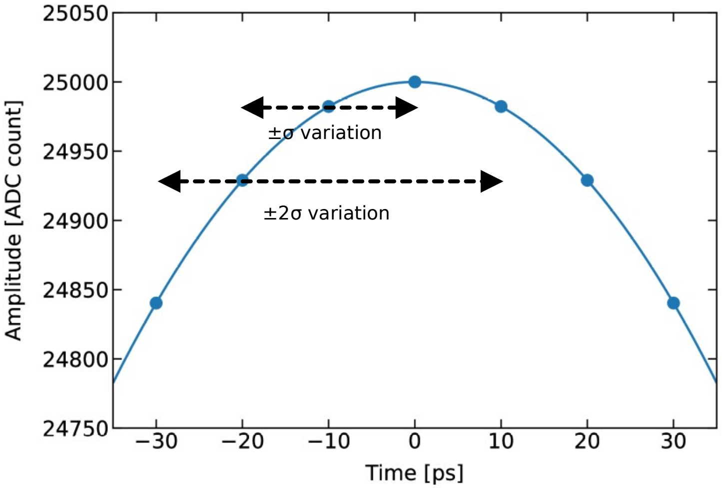
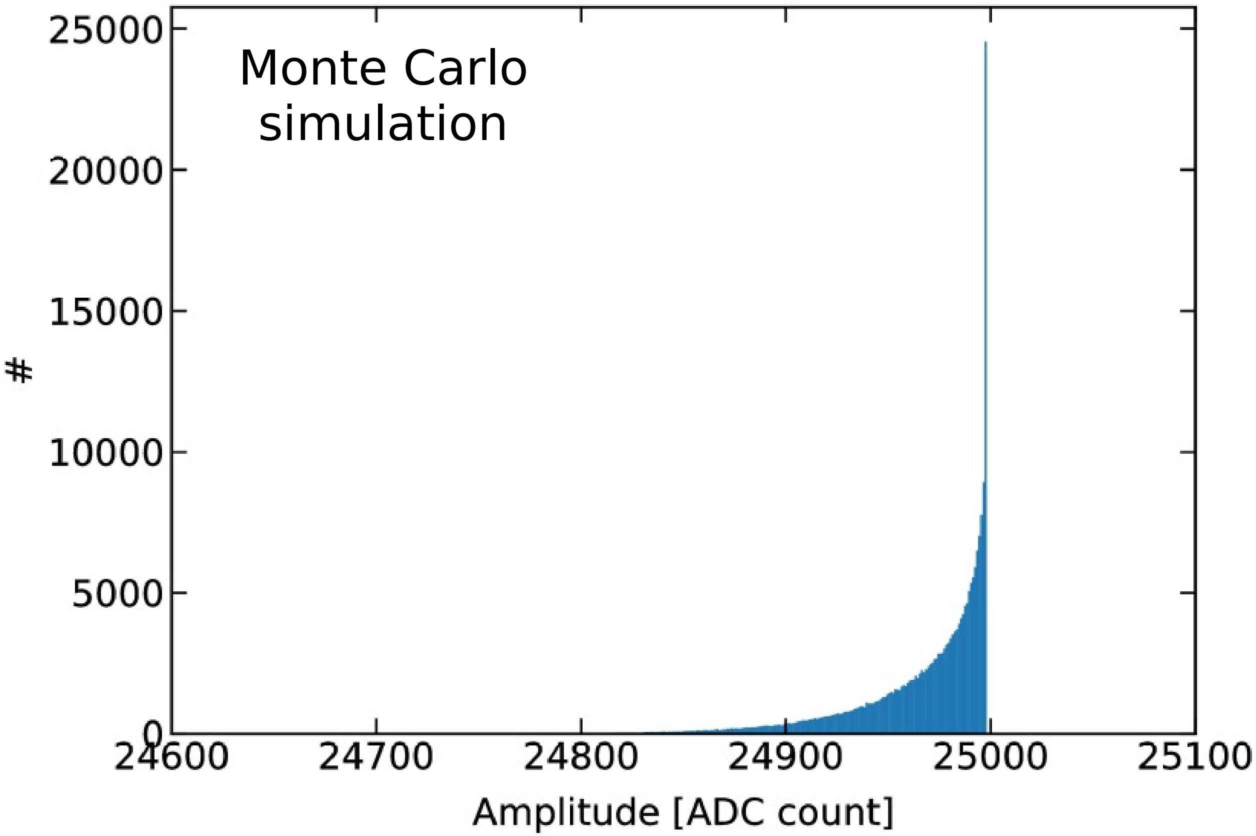
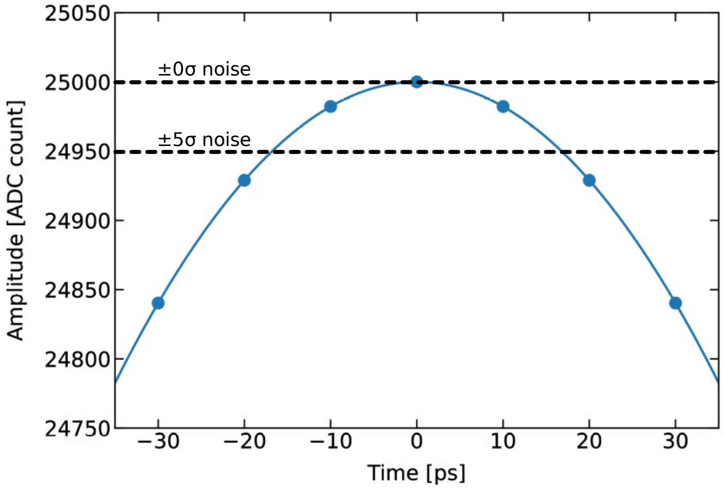


jitter + offset world:

moving about slope randomly following normal distribution with σ=10 ps

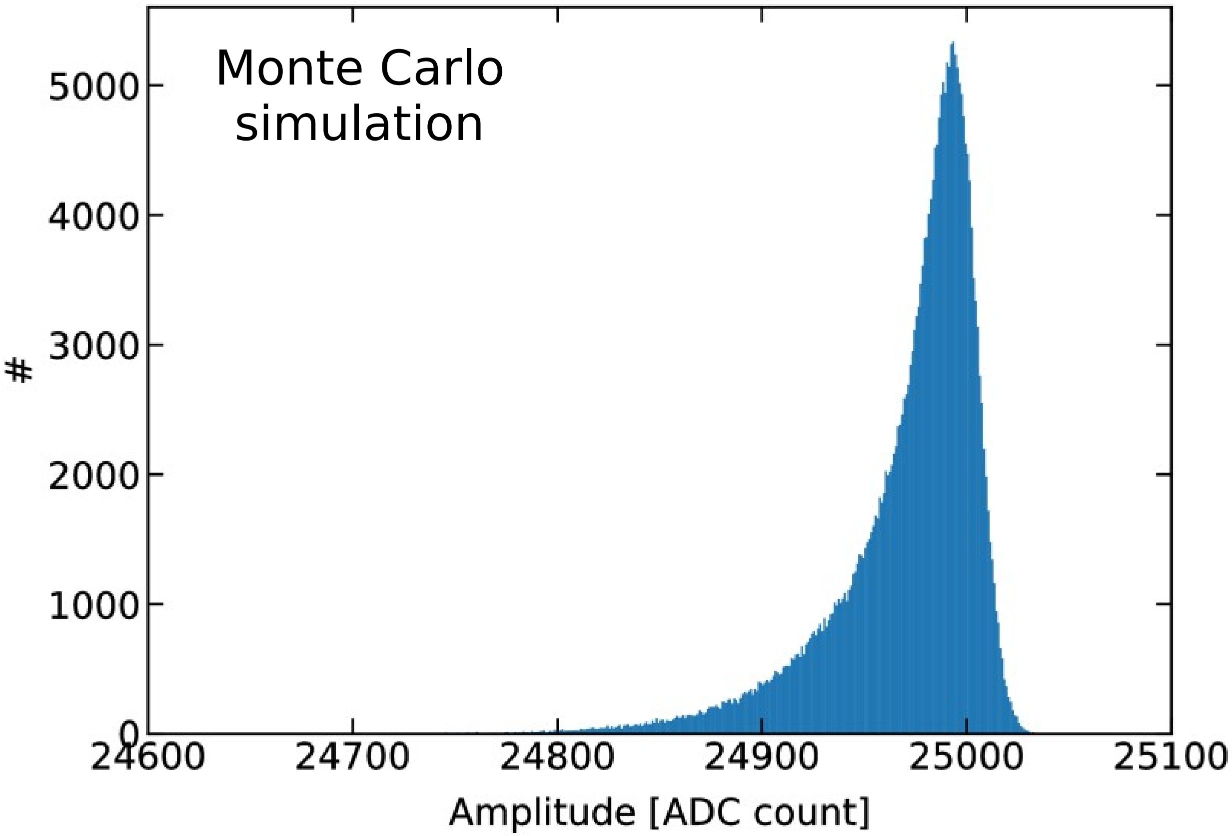


Reading out button amplitude for many consecutive turns provides us with a distribution that is shaped by error sources. Let's assume a **stationary beam**.

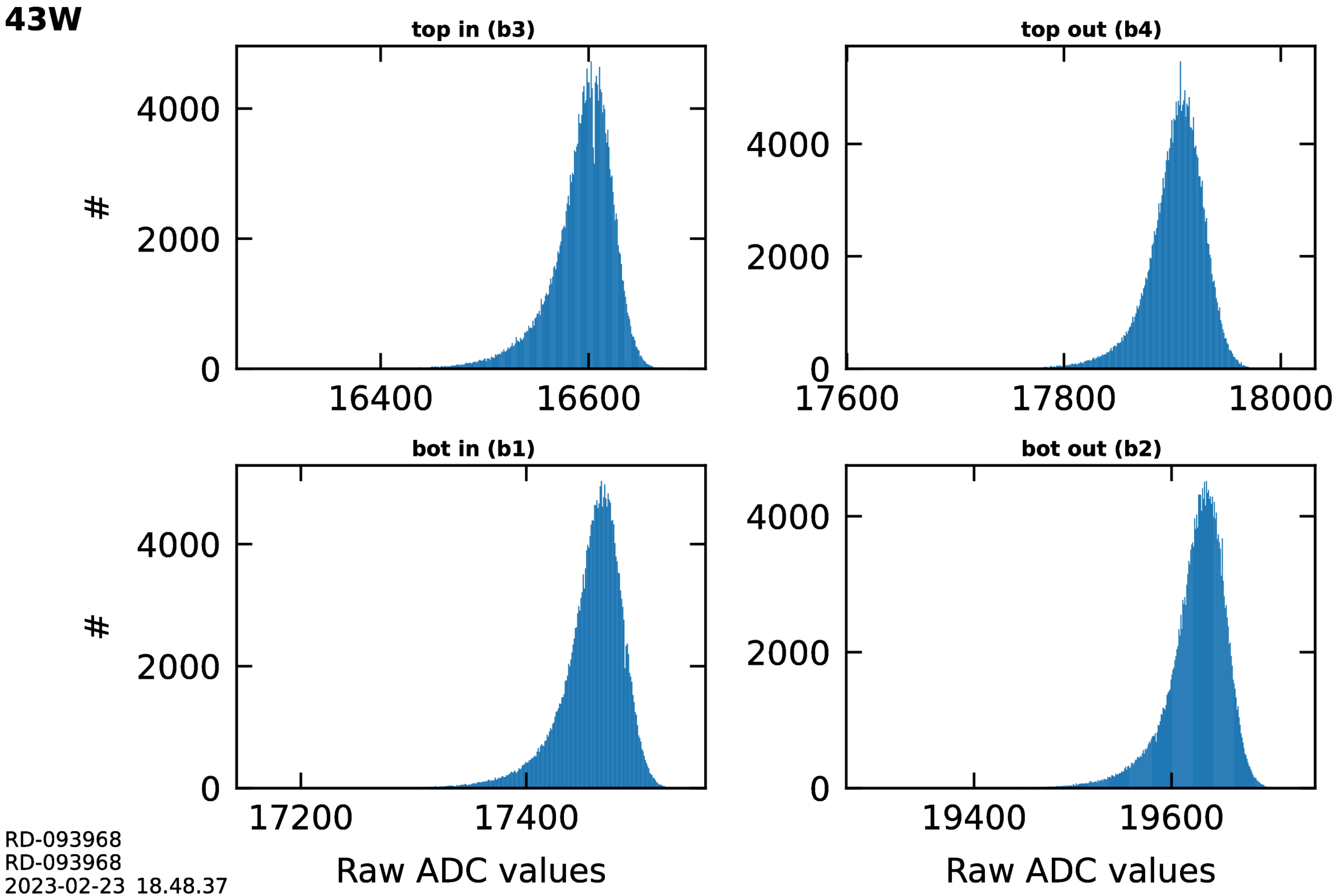


jitter + offset + noise world:

noise is normally distributed with width σ=10 ADC count → distribution smearing



Four buttons have uncorrelated error sources (independent from of each other)



Precision: error sources summary

Three error sources:

- ✗ peak-sampling alignment:
  - ➢ drift over time, need periodic timing (typically once a week)
- ✗ clock sampling jitter: normal distribution with σ=10 ps
- ✗ electronics noise: normal distribution with σ=10 ADC count

Other, more subtle effect:

- ✗ beam motion: affect peak-sampling alignment
  - ➢ motion amplitude-dependent precision
  - ➢ amplitude depends on β function → precision varies around the ring
- ✗ beam current:
  - ➢ varies by some ~5 %

Selected work:

in situ error measurement

Can we fit the button amplitude distribution?

Fitting the button amplitude distribution would give us *in situ* at each CBPM:

- ✗ measurement of the error sources
- ✗ measurement of the beam centroid motion
- ✗ data quality information (e.g.: do we need to time align?)

} all these things would be **new tools** for us to use!

The button distribution shape is the result of the convolution:

$$A \cdot \alpha_{\text{noise}} * \cos\left[\omega(t_j + t_0)\right]$$

where:

α_{noise} : electronics noise (random variable normally distributed noise)

t_j : sampling clock jitter (random variable normally distribution)

t_0 : peak-sampling alignment (fixed value)

After some math, one can find the PDF for cosine function of random variable t_j:

$$\cos\left[\omega(t_j + t_0)\right]$$

to be:

$$f_Y(y) = \frac{e^{-\frac{(acos(y)-\omega t_0)^2}{2(\omega\sigma)^2}}}{\omega\sigma\sqrt{2\pi(1-y^2)}} + \frac{e^{-\frac{(-acos(y)-\omega t_0)^2}{2(\omega\sigma)^2}}}{\omega\sigma\sqrt{2\pi(1-y^2)}}$$

where:

$$y \in [-1, 1]$$

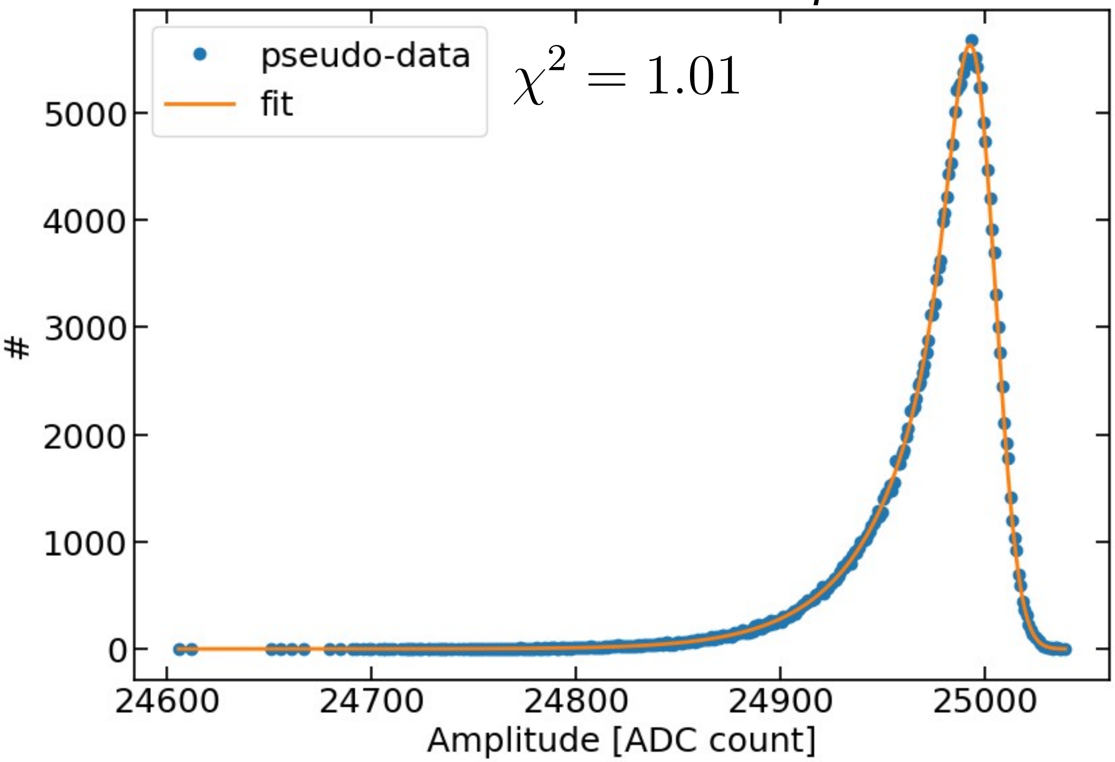
The convolution of the noise and cosine PDF is done via the Mellin convolution:

$$F(y) = \int_{-1}^{1} g(x) f(\frac{y}{x}) dx$$

Pseudo data generated randomly in a real data fashion (not using PDF):

- ✗ sampling clock jitter $\in [8, 12]$ ps
- ✗ peak-sampling alignment $\in [0, 30]$ ps
- ✗ electronics noise $\in [8, 20]$ ADC count
- ✗ waveform frequency $\in [480, 520]$ MHz
- ✗ waveform amplitude $\in [10000, 32000]$

one random pseudo data



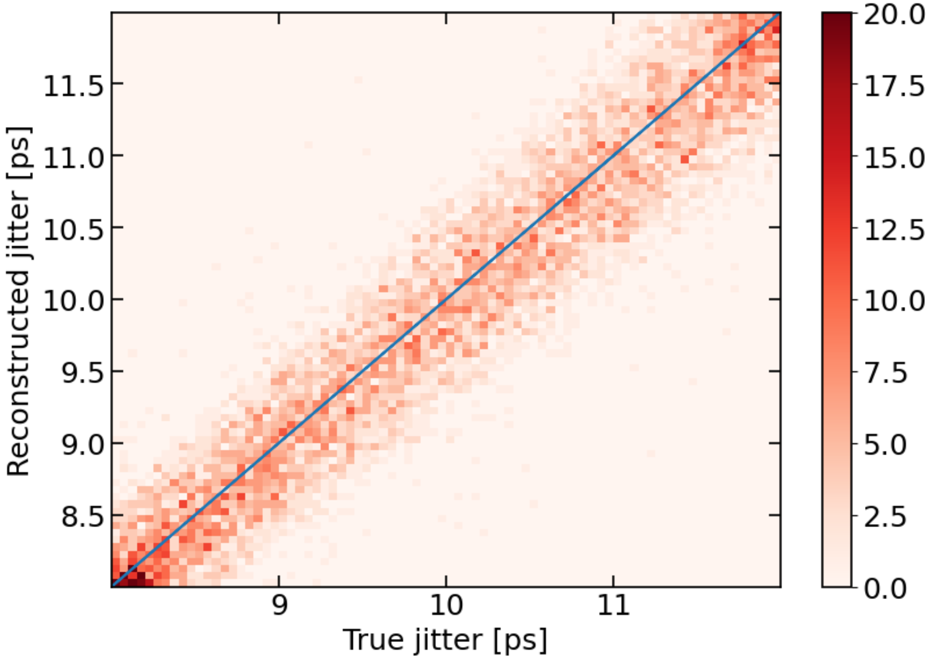
$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{n_i^{pred} - n_i^{meas}}{\sigma_i^{meas}}\right]^2$$

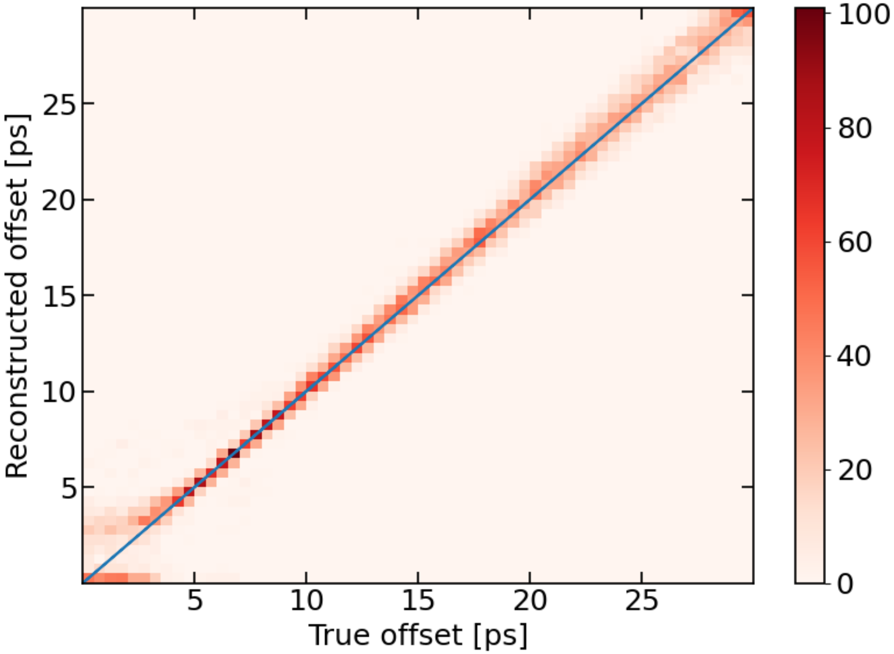
$$\sigma_i^{meas} = \sqrt{n_i^{meas}}$$

n_i : number of entries in i^{th} bin

Monte Carlo studies

10,000 pseudo-data was randomly generated simulating 262,144 turns (i.e. 2^{18})





	precision	accuracy
jitter [ps]	0.35	0.01
offset [ps]	0.90	-0.16
noise [ADC count]	0.46	0.03
amplitude [ADC count]	1.26	-0.322

Current status: work in progress

First attempt at using method on real-life button distribution:

✗ revealed limitation off the bat: fit does not include beam centroid motion

✗ beam centroid motion was added as yet an other normal distribution

Button distribution from actual data can always be fitted with "satisfaction" but:

✗ are the fitted parameter meaningful?

✗ "degeneracy" issue where different set of parameters yield same distribution

✗ more Monte Carlo simulation is needed

Collected data varying in a known fashion:

✗ beam centroid motion

✗ peak-sampling alignment

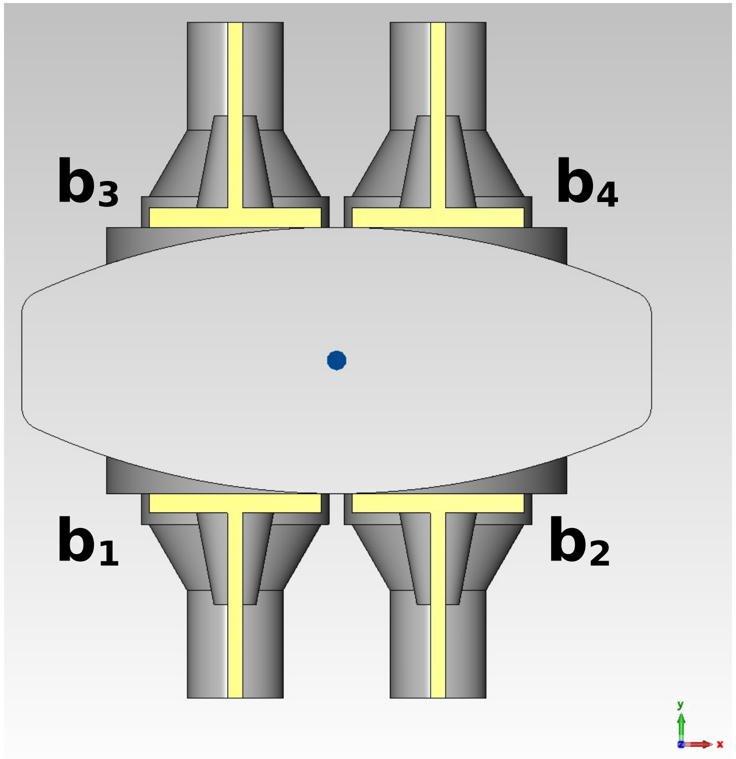
✗ goal: retrieve known parameters while having other ones not changing → it would prove the method to be meaningful

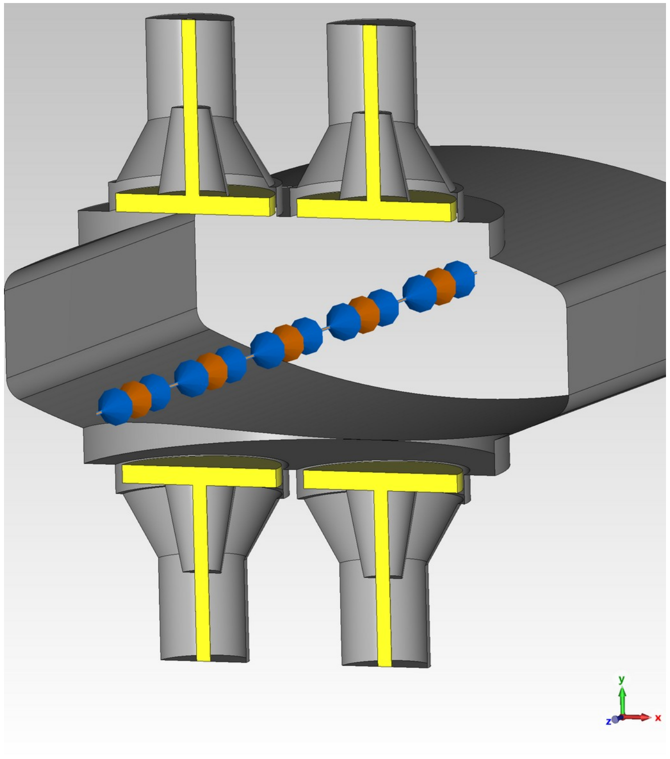
Nonlinear beam position reconstruction

CESR Beam Position Monitor (CBPM)

Measure beam position at about 100 locations along the 768 meter storage ring

"North Arc" BPM geometry modeled in CST microwave studio





Beam position (e.g. horizontal) can be reconstructed linearly via:

$$x = k_x \frac{(b_2 + b_4) - (b_1 + b_3)}{b_1 + b_2 + b_3 + b_4}$$

where k_x is a factor accounting for the vacuum chamber geometry

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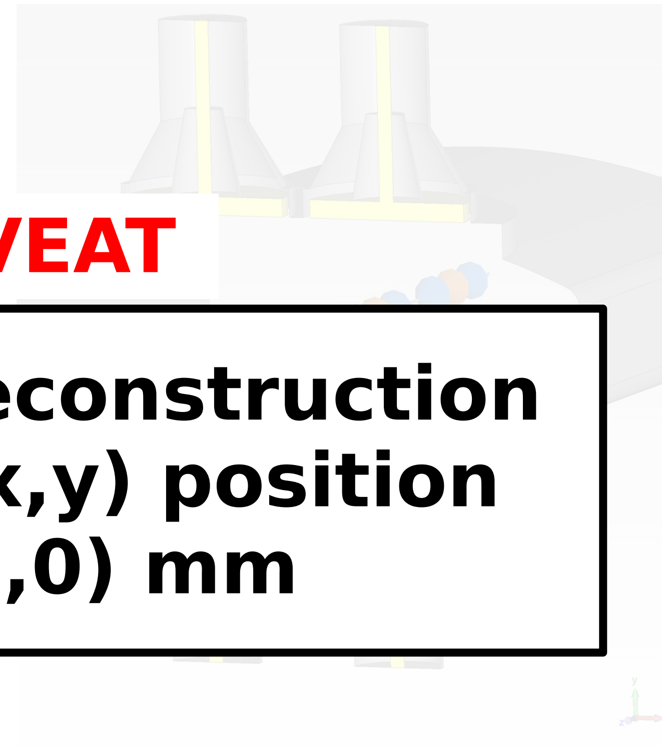


BIG CAVEAT

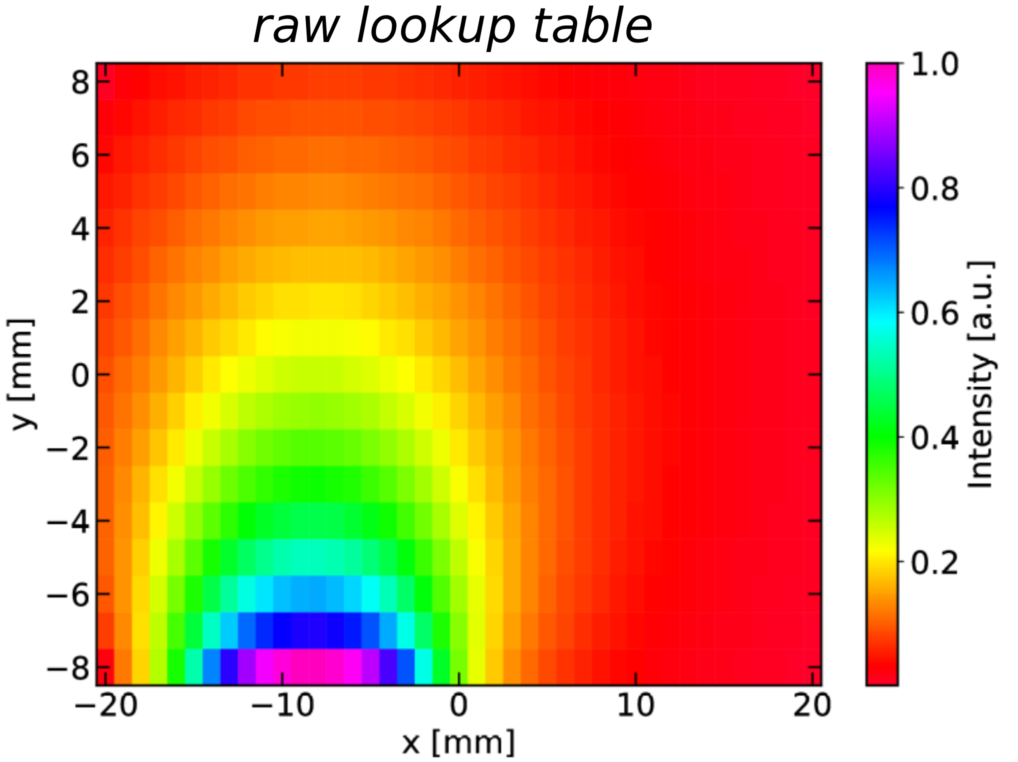
linear position reconstruction only valid for (x,y) position close to (0,0) mm

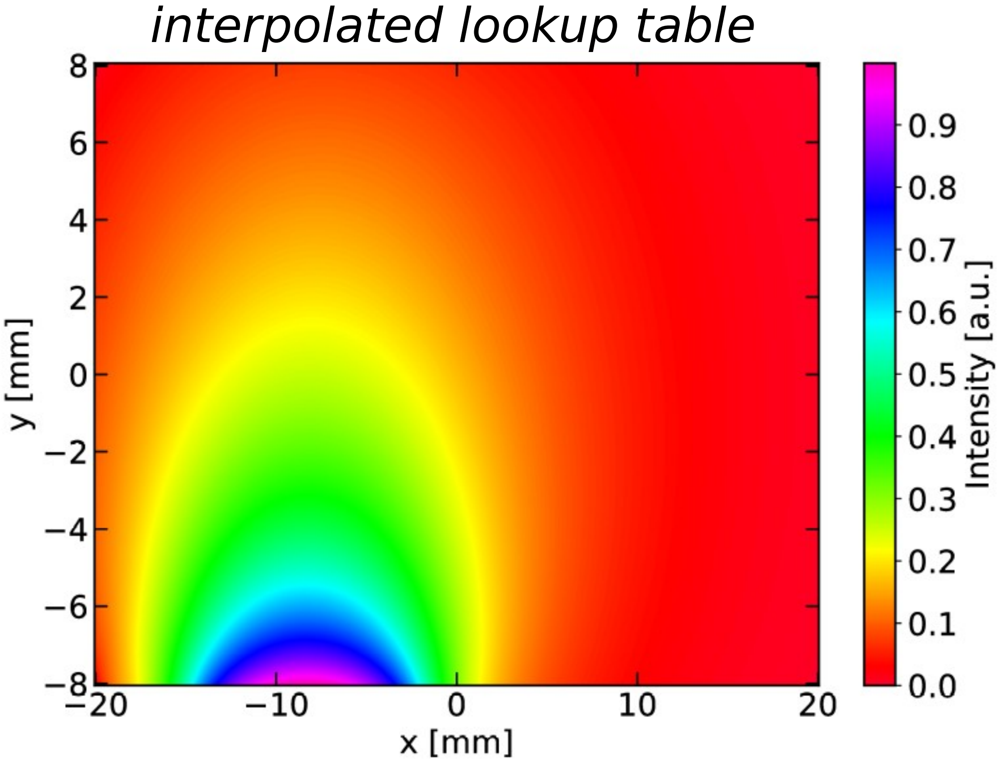
Beam position (e.g. horizontal) can be reconstructed linearly via:

$$x = k_x \frac{(b_2 + b_4) - (b_1 + b_3)}{b_1 + b_2 + b_3 + b_4}$$

where k_x is a factor accounting for the vacuum chamber geometry

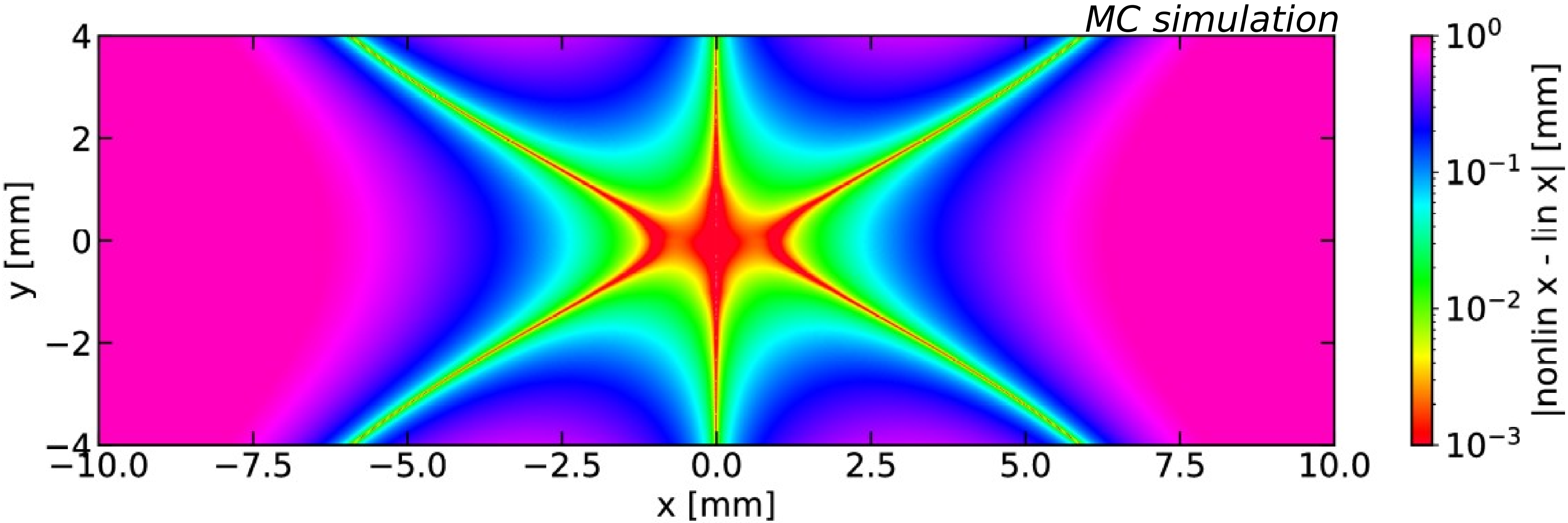
Button response to (x, y) bunch position simulated using Poisson's equation (2D static), see Hoffstaetter, Helms (2005). For **south arc** chamber geometry:

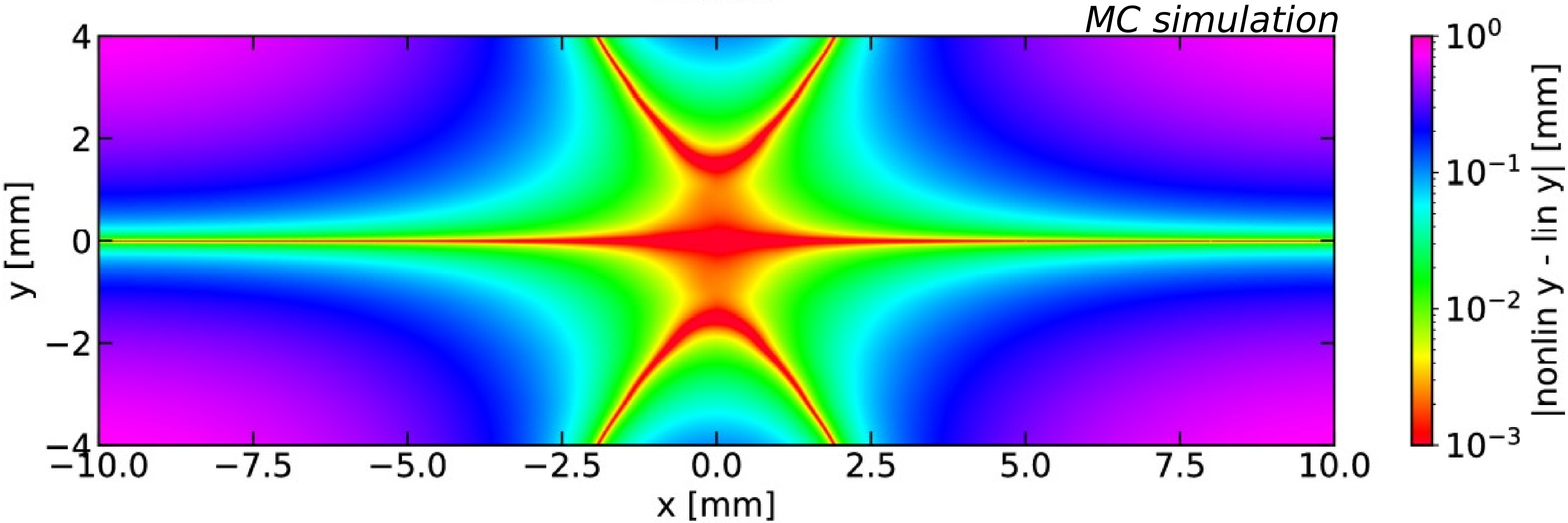




Clearly the linear position reconstruction will be inaccurate for off-centered beam

Linear vs nonlinear position reconstruction





Nonlinear position reconstruction

The position reconstruction relies on solving the system:

$$\begin{aligned} b_1 - f_{b_1}(x,y) &= \epsilon \to 0, \\ b_2 - f_{b_2}(x,y) &= \epsilon \to 0, \\ b_3 - f_{b_3}(x,y) &= \epsilon \to 0, \\ b_4 - f_{b_4}(x,y) &= \epsilon \to 0 \end{aligned}$$

<u>Where:</u>

b_i is the measured button amplitude

$f_{b_i}(x,y)$ is the simulated button response (Poisson look-up table)

The system is determined (4 equations, 2 unknowns) → can be solved no problem

Implemented as a minimization:

$$\text{f.o.m.} = \sum_{i=1}^{4} \left[b_i - f_{b_i}(x,y)\right]^2$$

Where:

b_i is the measured button amplitude

$f_{b_i}(x,y)$ is the simulated button response (Poisson look-up table)

Recent work

Nonlinear position reconstruction is not new and has been available to us in Fortran since 2005, see Hoffstaetter, Helms (2005)

Recently:

- ✗ implemented independent method (in Python as opposed to Fortran)
- ✗ extensive and thorough performance comparison between two methods

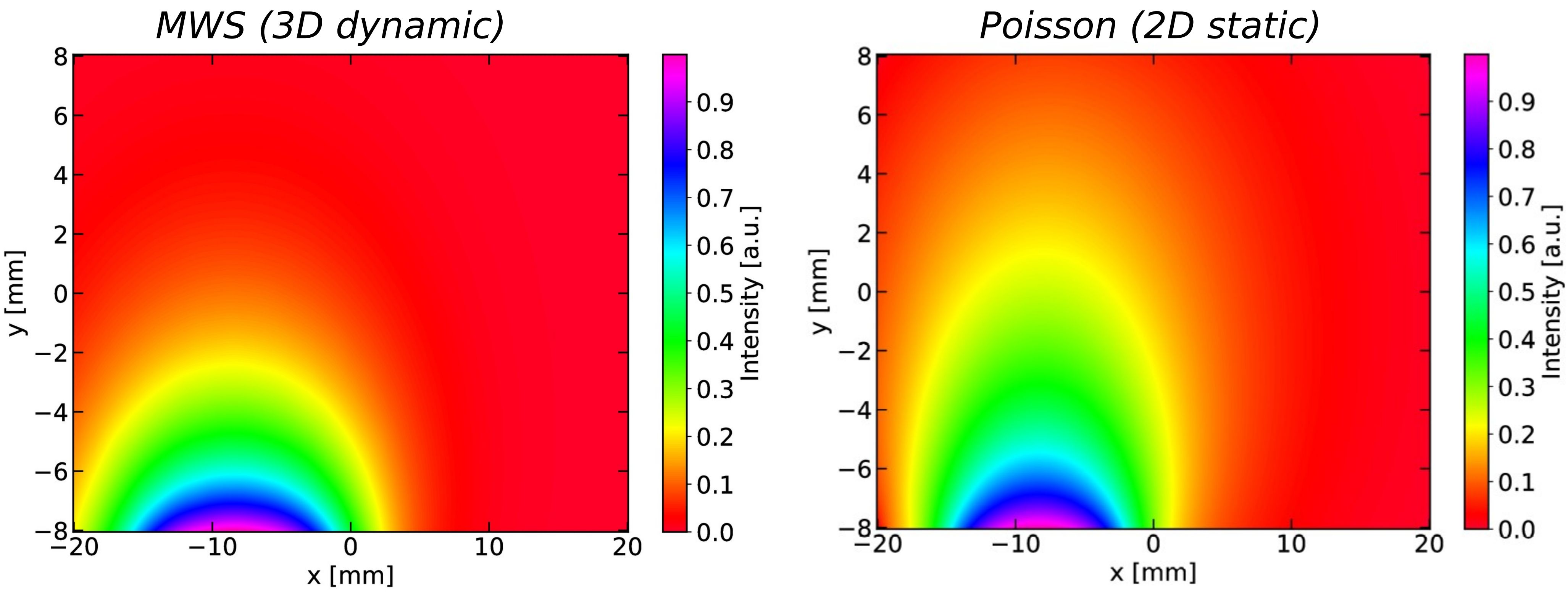
Outcome:

- ✗ Fortran's performance was improved after code update
- ✗ new feature added:
  - position reconstruction with only 3 buttons
  - very useful as we do have individual button failing

Topics for an other time

Beam position accuracy

Position reconstruction relies on button response map: let's compare map



Different button responses affect differential orbit measurements:

- ✗ orbit difference will have a different value depending on which map is used
- ✗ we are talking about differential orbit accuracy

Button relative gain calibration

Not calibrating relative button gain results in degrading beam position accuracy by several hundred microns

<u>New method developed:</u>

- ✗ fit simultaneously for (x,y) beam positions and button relative gain
- ✗ collect data for 9 beam positions on a ±1 mm grid
- ✗ method precision below 0.1%
- ✗ good alternative/complement to David Rubin et al. (2010) ‘s method

$$\text{f.o.m.} = \sum_{i=1}^{9} \left[\sum_{j=1}^{4} \left[b_{ij} - \frac{f_{b_{ij}}(x_i, y_i)}{\alpha^{gain}{}_j} \right]^2 \right]_i$$

We fit for 9 (x,y) pairs and 3 gain values: **21 parameters total**

REU 2021: weblink to paper

Leveraging the Power of Neural Network AI to Improve the Precision on the Beam Position Reconstruction at CESR

Anna Nica[1] and Antoine Chapelain[2]

[1] *University of Colorado, Boulder, CO 80309, USA*
[2] *CLASSE, Cornell University, Ithaca, NY 14850, USA*

(Dated: August 2021)

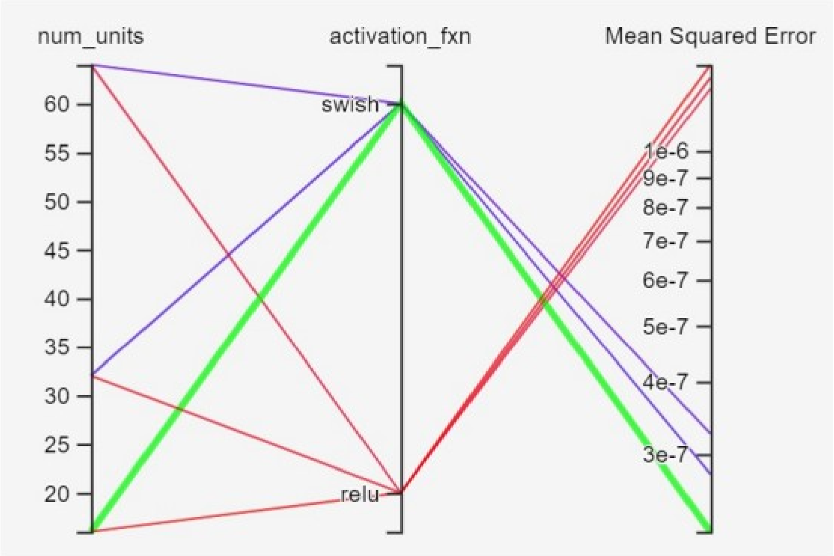


Figure 4: Results of the hyperparameter optimization for the hyperparameter combinations tailored for the final scan. Created using Tensorboard (Abadi et al. 2015).

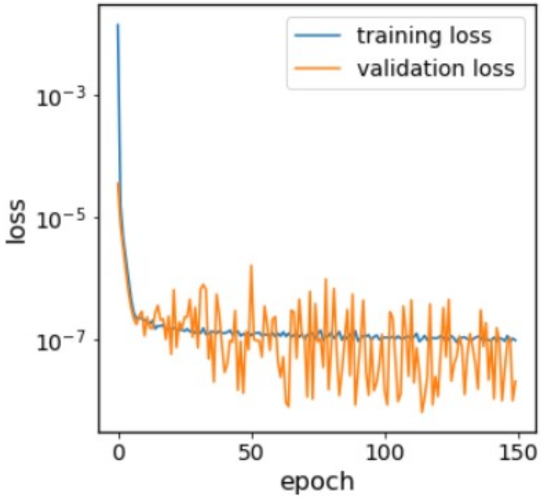


Figure 7: Loss per epoch of neural network training for the neural network with best accuracy (represented by the green line on Figure 4). Validation loss generally follows training loss, suggesting the network can reproduce similar results using input data it has not been trained on.

Machine learning at CESR: ramping up II

Trying to turn Vardan's dipole noise kick finding method → neural network

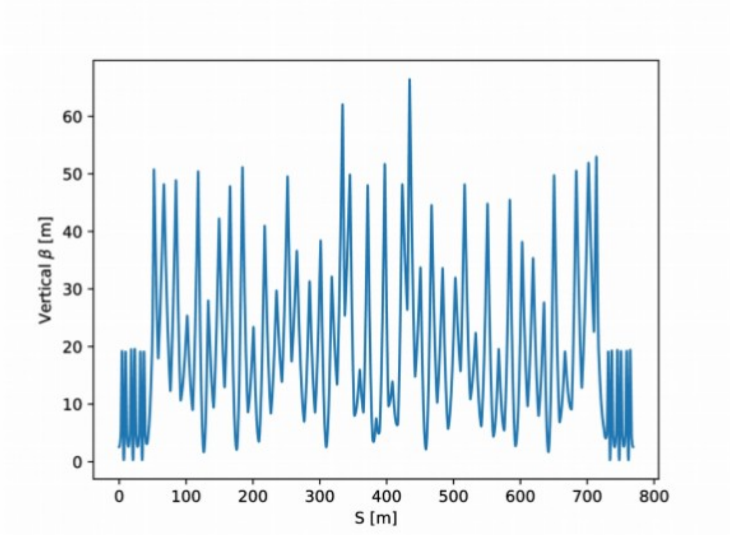
Why going the Neural Network (NN) route?

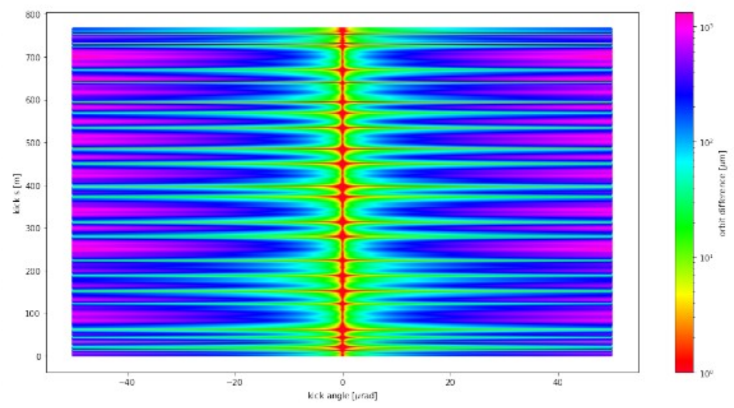
1) The problem at hand is a non-linear regression

$$\sum_j \theta_j \cdot \frac{\sqrt{\beta(s)\beta(s_j)}}{2\sin(\pi Q_x)} \cos[|\phi(s) - \phi(s_j)| - \pi Q_x],$$

θ_j - is the j-th kick angle

s_j - is the j-th kicker position



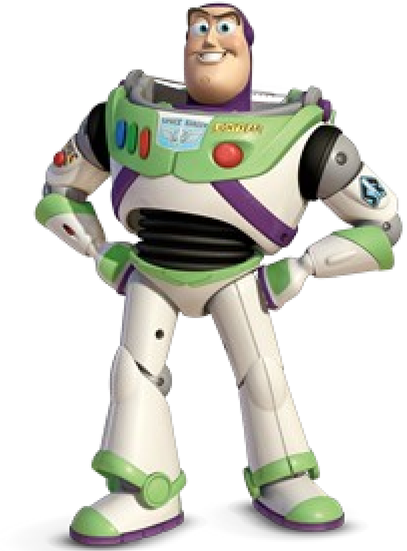


2) We can generate simulated date using our model (formula)

→ this plays nicely into NN strength for supervised non-linear regression problem, especially the Multi-layer Perceptron (MLP) network

From CBPM-2 to CBPM-3:

“to Infinity and Beyond”



Toward CBPM-3

CBPM-2 issue:

- ✗ hardware fails from aging/radiation: almost no spare electronics left
- ✗ part of electronics is obsolete… cannot buy/make more
- ✗ need new hardware → **CBPM-3 upgrade**

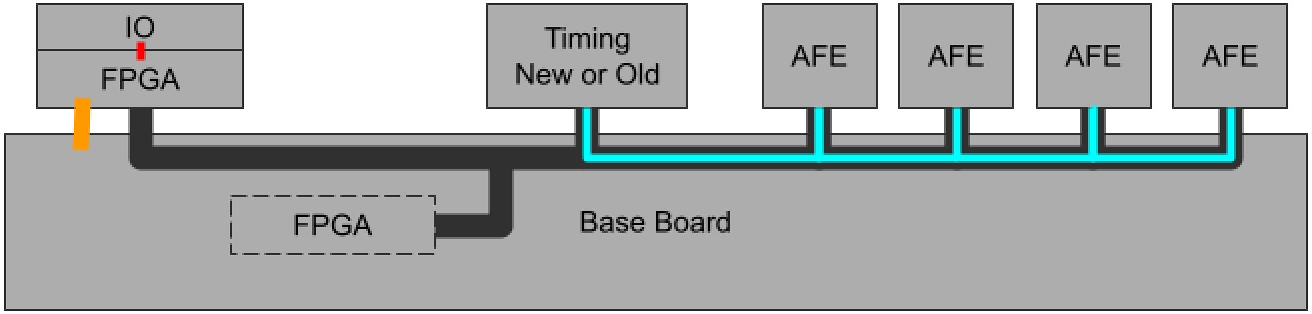
CBPM-3's design:

- ✗ 10 Hz continuous orbit monitoring with real-time live display/analysis
- ✗ micron-level precision on x/y beam position via hardware-level turn averaging
- ✗ fast response position interlocking to protect equipment high intensity beam
- ✗ requires new hardware, firmware, software, analysis, monitoring…

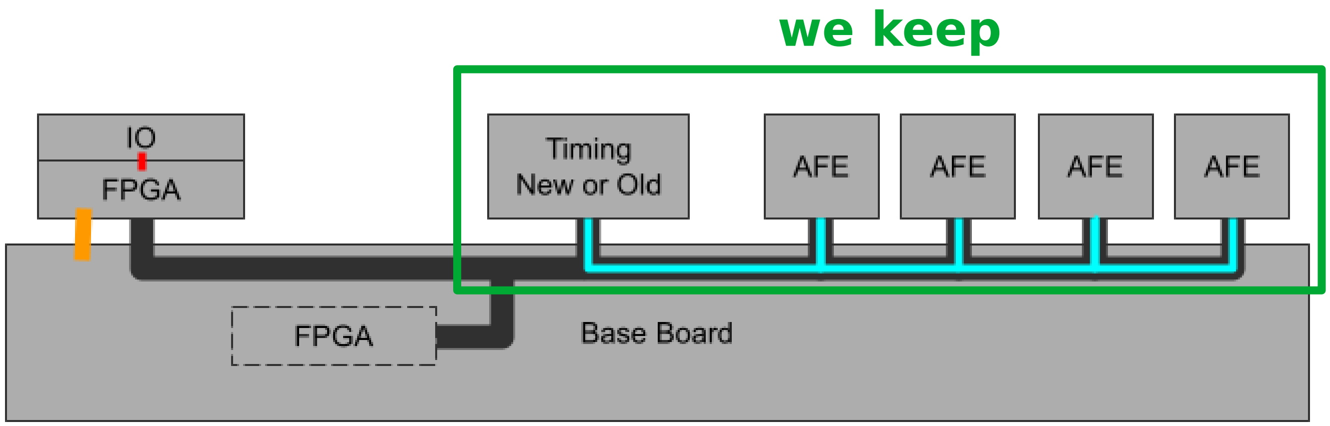
Deployment:

- ✗ first priority is to replace failing CBPM-2 electronics with CBPM-3 upgrade
- ✗ roll out new capabilities in a staged approach

CBPM-2 backplane and I/O boards are obsolete

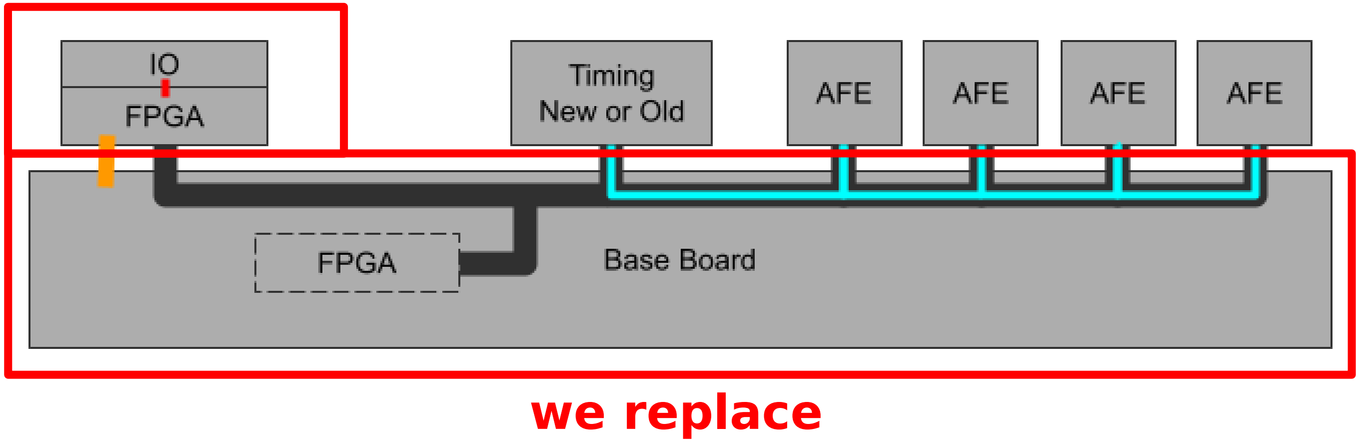


CBPM-2 backplane and I/O boards are obsolete



Replacing obsolete hardware

CBPM-2 backplane and I/O boards are obsolete



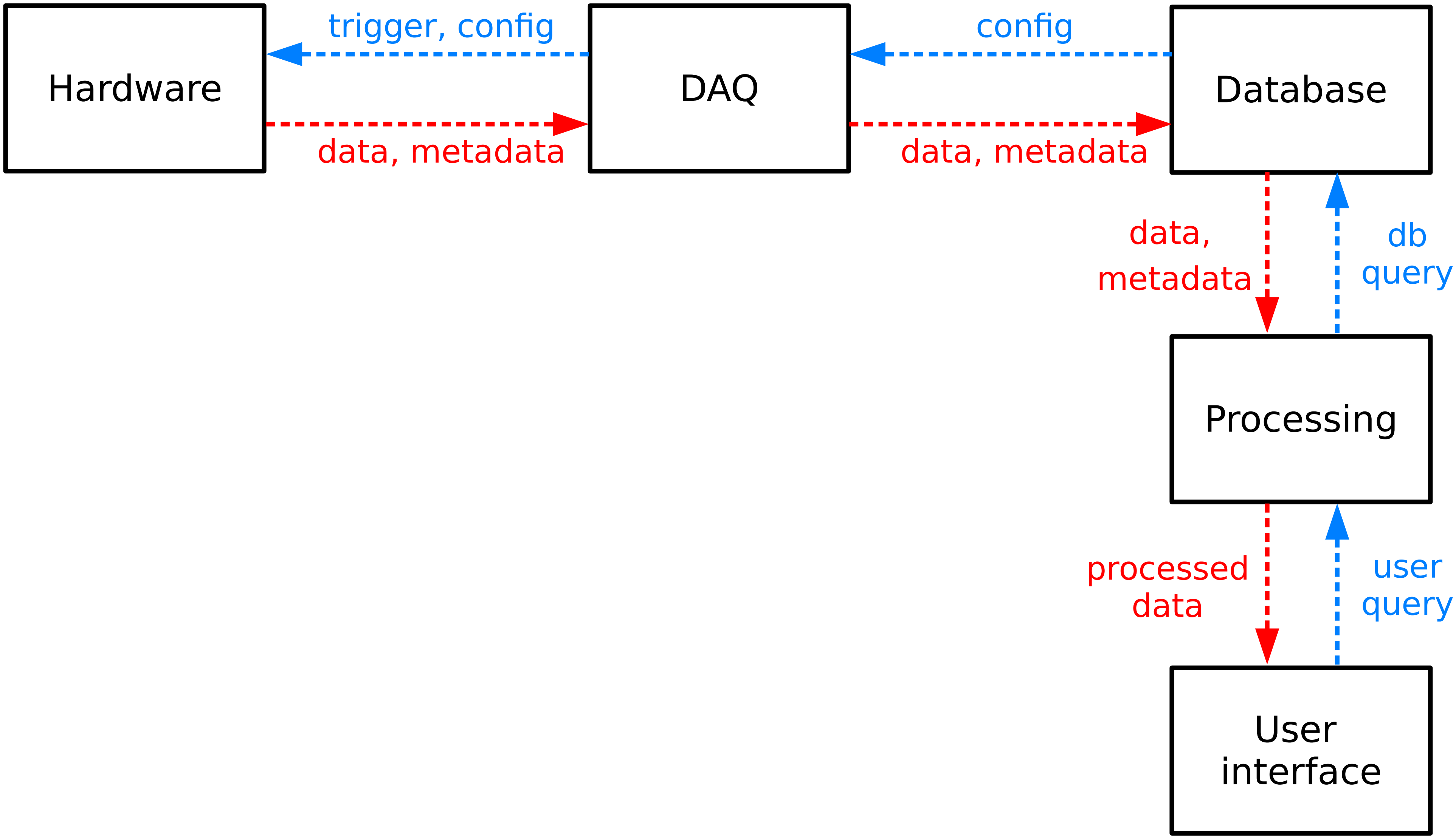
New backplane will be passive (no processing)

New I/O board responsible for all the processing using Enclustra's Mars ZX2:

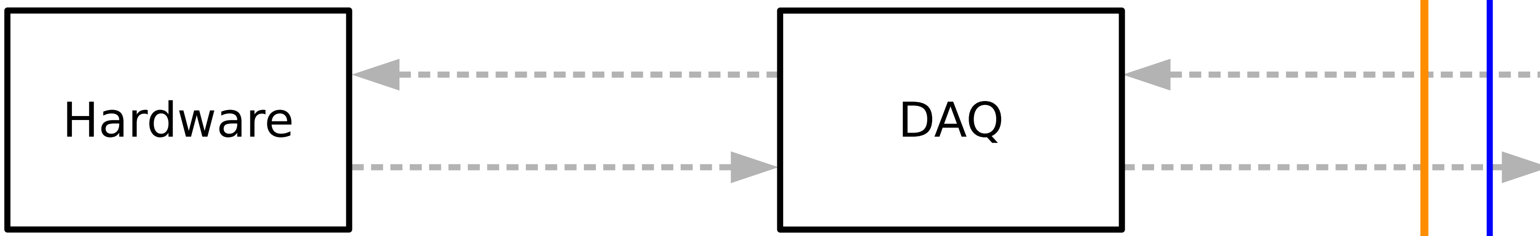
✗ Zynq SoC: FPGA + CPU processor → onboard Linux OS

- help simplifying the design being "all-in-one"
- better network : higher data throughput and communication reliability

CBPM3 system design



Full stack web dashboard

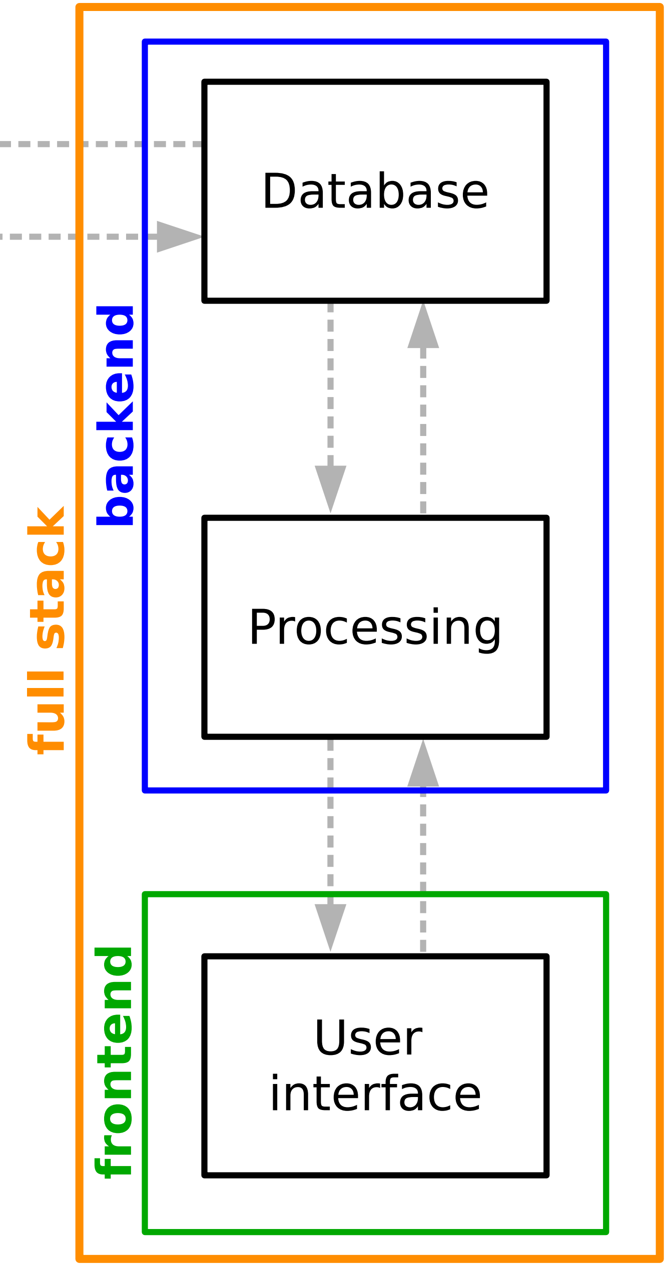


Full-stack web-app to monitor current/past data

- ✗ back-end (server side): database storage for data and metadata, data processing and analysis
- ✗ front-end (client side) : web-browser user-friendly interface to display and interact with monitoring information (analyzed data, data quality, alarms/warnings)

To hear more about it, see Zoom recording of presentation given at:

CHESS scientific computing, February 16 2023



New peak-alignment algorithm

Current algorithm looks for maximum amplitude:

- ✗ measurement uncertainty → maximum amplitude ≢ waveform peak

Paths to improvement:

- ✗ select time step with smallest RMS (expected smallest at the peak)
- ✗ quadratic fit to the peak
- ✗ play with how many data points are averaged at each time step
- ✗ *in situ* error measurement at each time step

Hardware potential for precision improvement

Any effort that could reduce the impact of electronics noise, sampling clock jitter, and peak-alignment → higher precision

We are exploring/looking into revamping analog frontend board (AFE):

- ✗ CESR operates differently now that it is fully dedicated to CHESS:
  - ➢ only one species (positrons) with 14 ns bunch spacing
- ✗ AFE could be revamped to take advantage of new running conditions to:
  - ➢ significantly reduce the RMS noise
  - ➢ provide a lot more signal amplification → enable orbitry during CESR startup
  - ➢ current AFE board are operational but damaged by aging/radiation

An other important avenue would be to upgrade the timing board:

- ✗ reduce sampling clock jitter: 10 → xx ps?
- ✗ provide finer time stepping: 10 → xx ps?

Talk's conclusion

CBPM-2:

- ✗ its behavior, precision and accuracy are well understood
- ✗ several on-going efforts to improve it further
- ✗ reached obsolescence

CBPM-3:

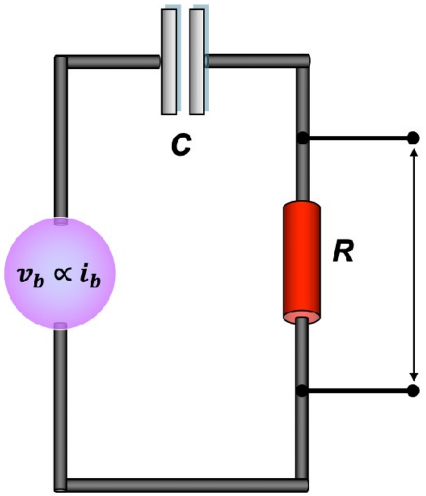
- ✗ under development: will replace CBPM-2 in the coming years
- ✗ nominal design will provide better performance and tools
- ✗ potential for even more improvement via software/hardware R&D effort

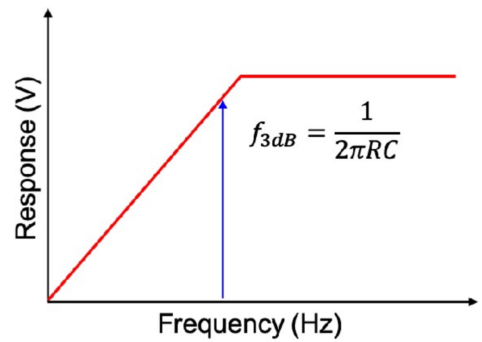
Machine learning:

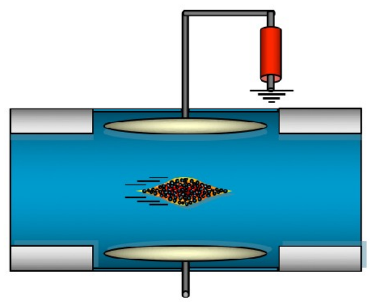
- ✗ we have a lot of data → usher new era using ML to improve CESR
- ✗ CBPM3 will offer even more and higher rate data
- ✗ can lean on local expertise (e.g.: Georg and Lucy)

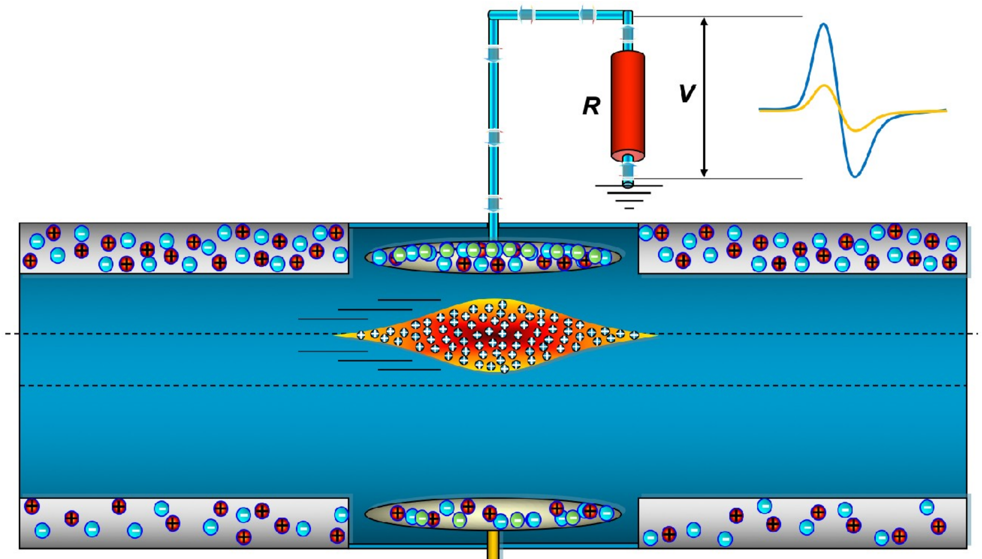
Additional materials

Beam position is the heartbeat of particle accelerators: its measurement is non-destructive and rely on picking-up beam’s image charges (currents)









arXiv:2005.14081

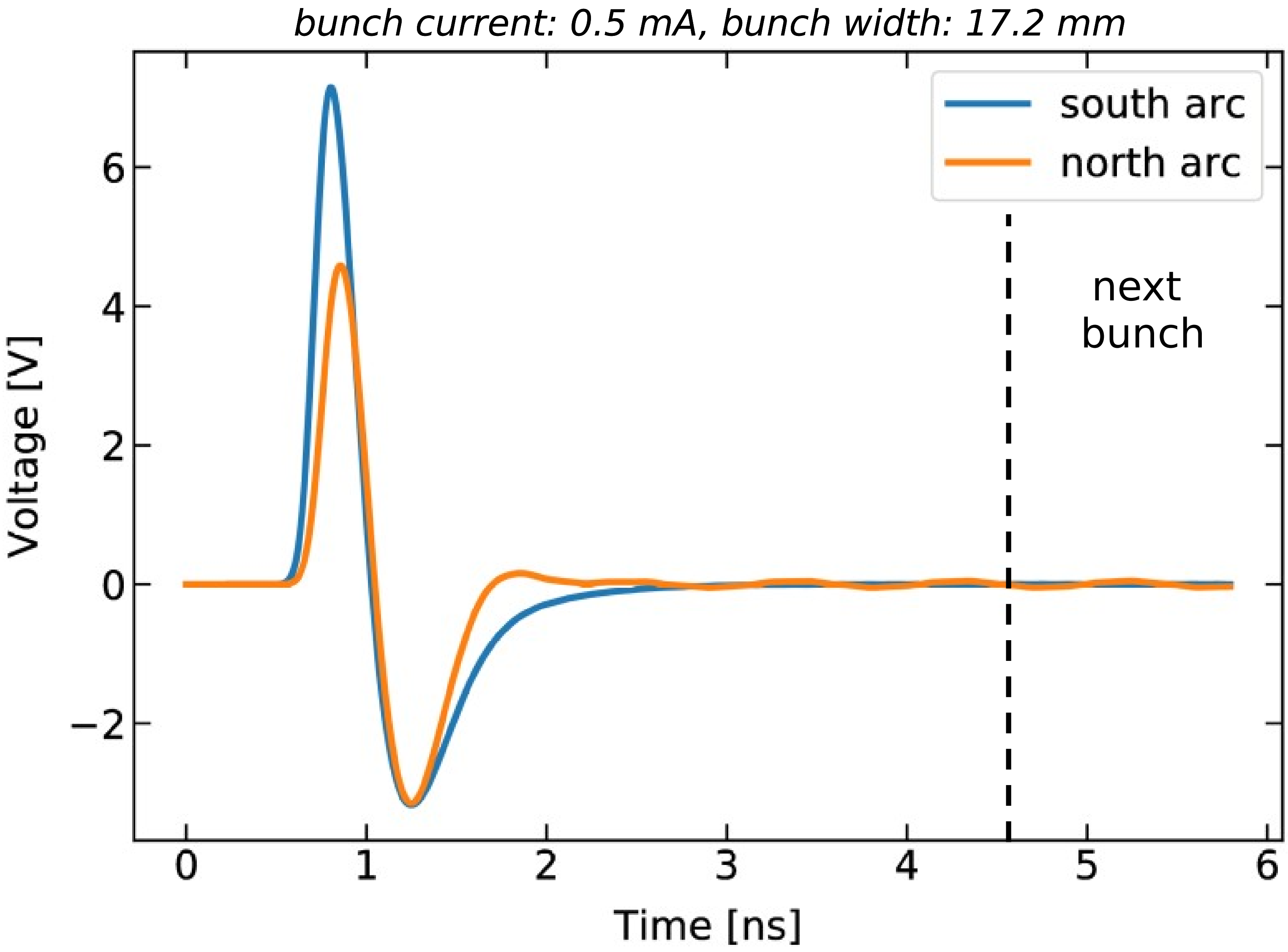
Coin-like shape capacitive pick-up electrodes (aka “buttons”) generate waveform signal for each passing charged bunch → digitized by readout electronics

BPM system = **pick-up electrodes** + **readout electronics**

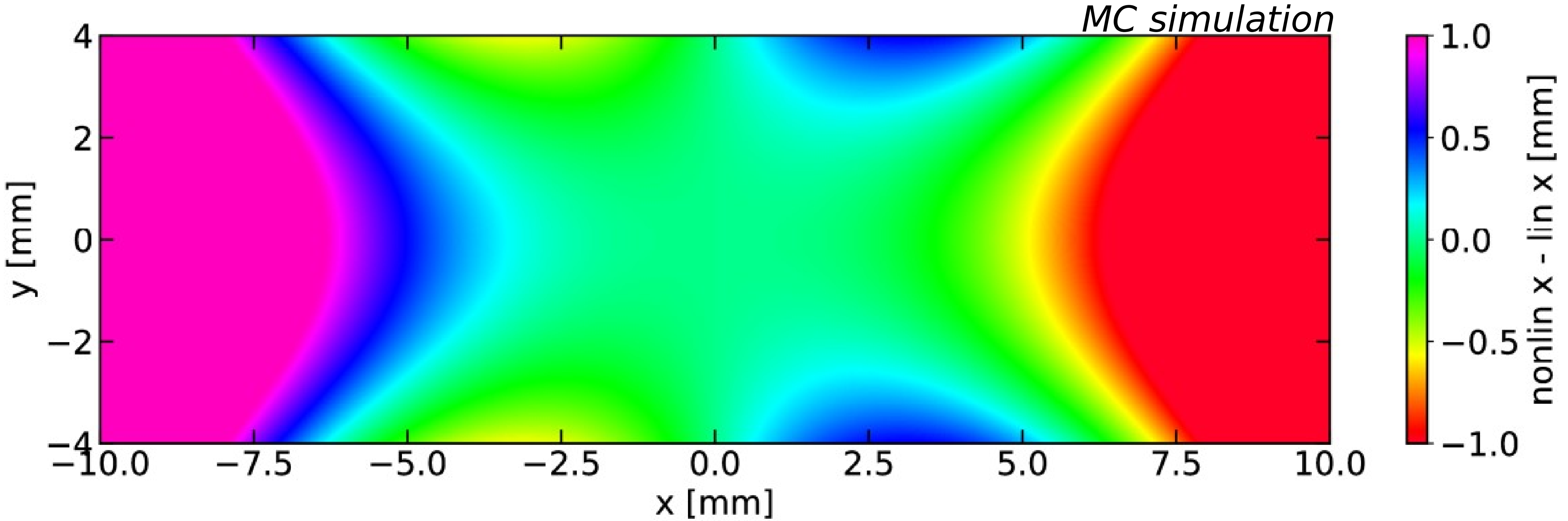
Signal intensity difference between symmetrically placed electrodes allows reconstructing beam position

Expected button response to bunch passing by

Waveform entering read-out electronics after 1.2 GHz low-pass filtering



CST Microwave studio wakefield simulation


MC simulation
4
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−2
−4
y [mm]
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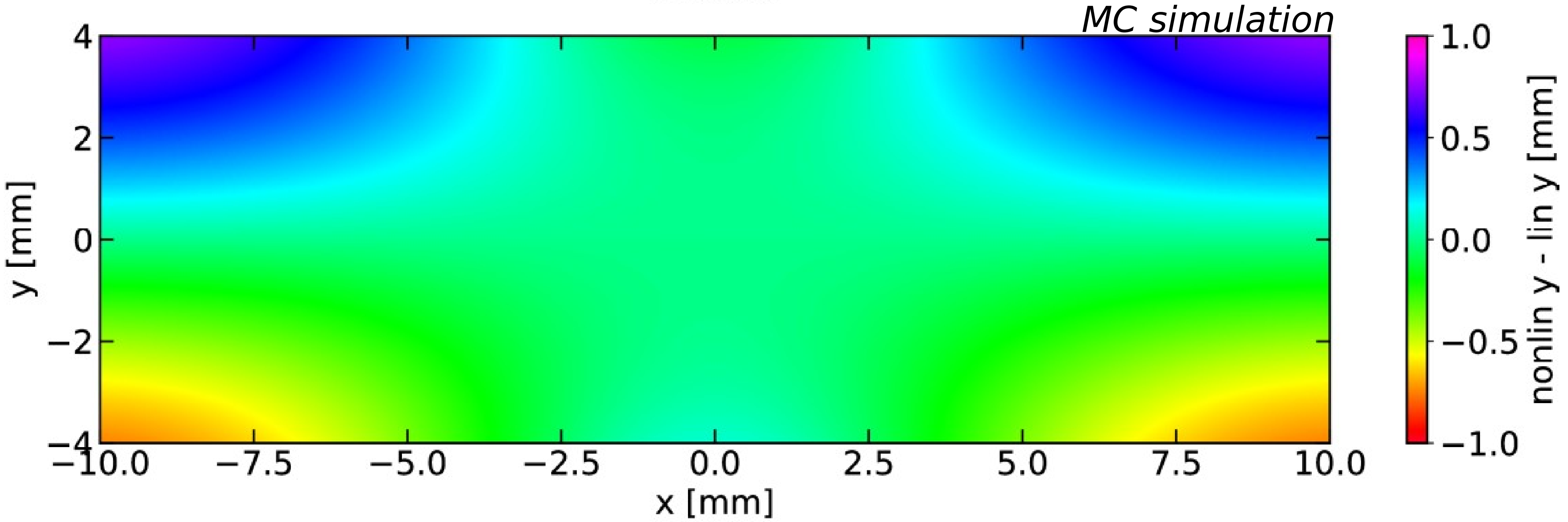
MC simulation
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