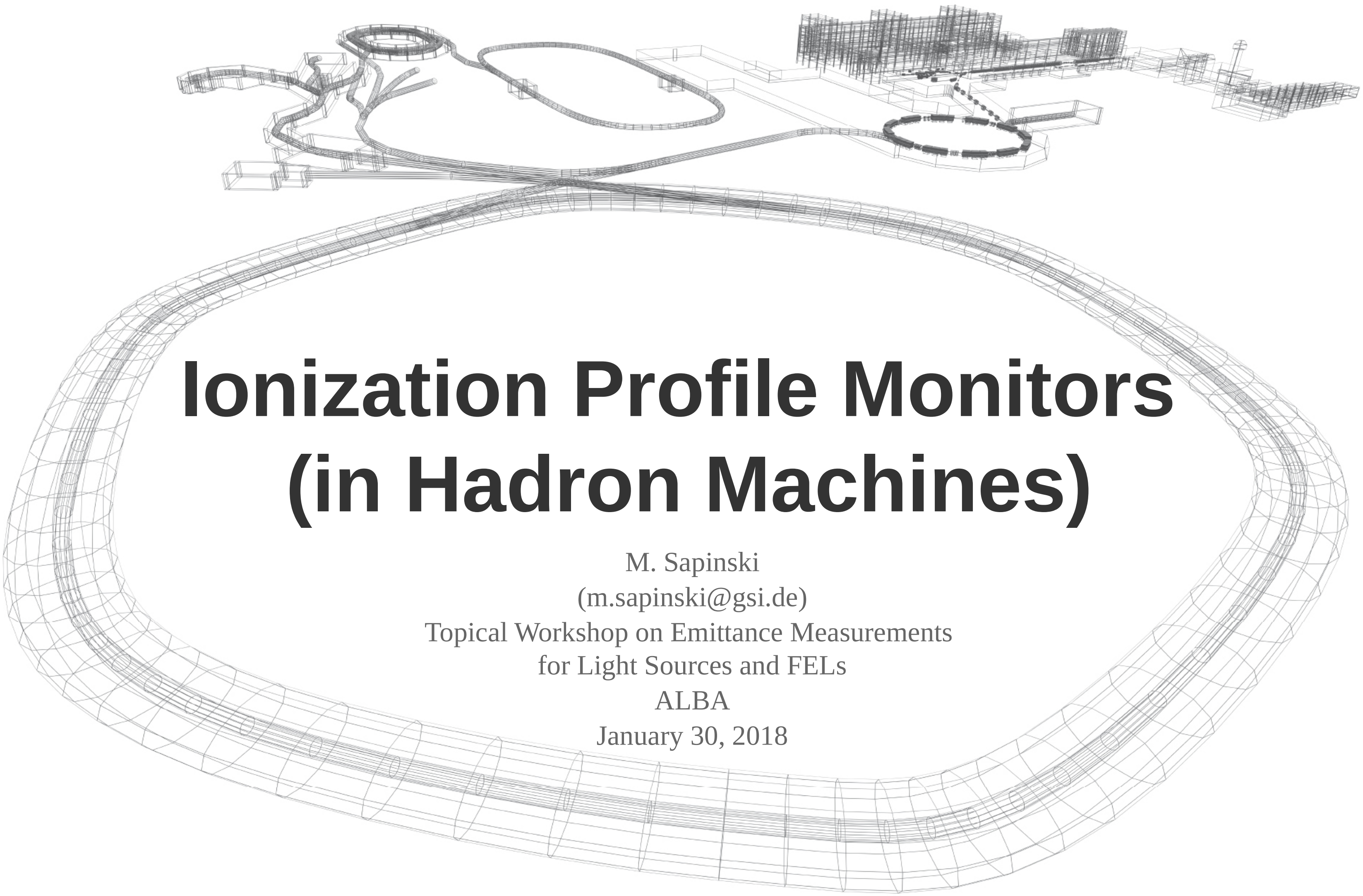

Ionization Profile Monitors (in Hadron Machines)

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Topical Workshop on Emittance Measurements
for Light Sources and FELs
ALBA
January 30, 2018

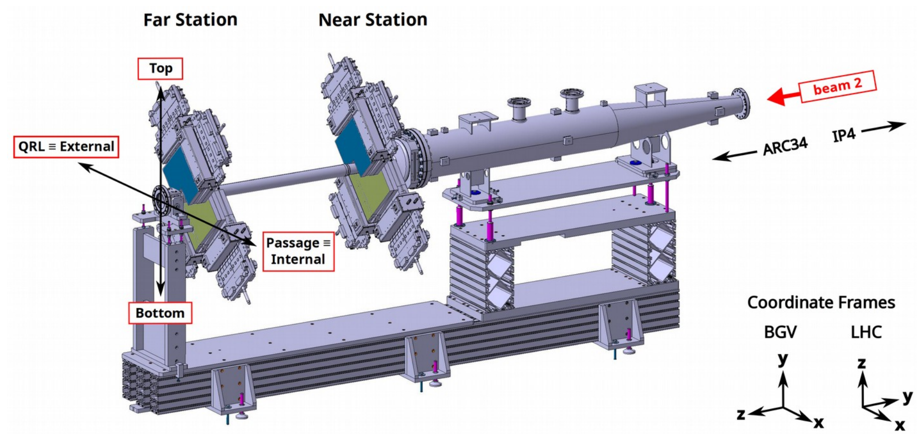
- Report on recent developments in Ionization Profile Monitors which maybe of use for electron machines

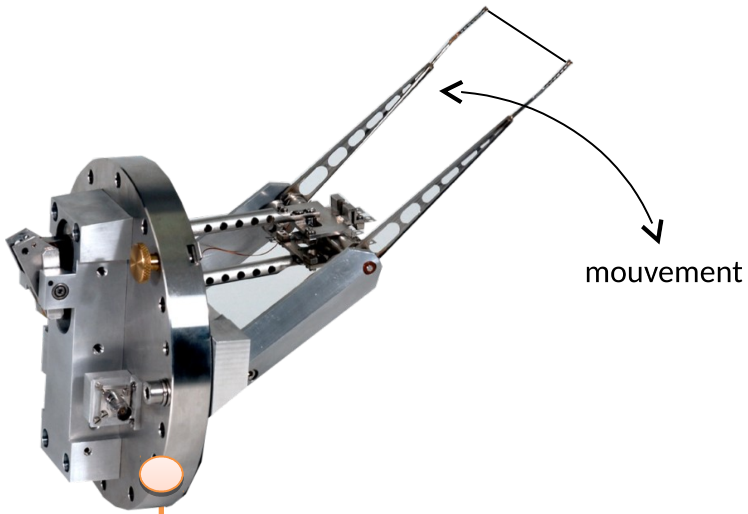
Outline

- Introduction: noninvasive beam profile measurement (in hadron machines)
- Ionization Profile Monitors with examples
- New readout based on Hybrid Silicon Pixel detector
- Typical issues and limitations
- IPM for Light Source – ALBA case study
- Correction to profile distortion using Machine Learning
- Conclusions

Noninvasive beam profile measurements (I)

- At very high energies (LHC)
  - synchrotron radiation
- “Thin gas targets”:
  - **Beam-Induced Fluorescence monitors (BIF),**
  - **Wire Scanners,**
  - **Ionization Profile Monitors**
  - Beam Gas Vertex detector (>GeV energy)
- Electron wire scanners
- Laser wire scanners (LINAC4, H-)
- Shottky

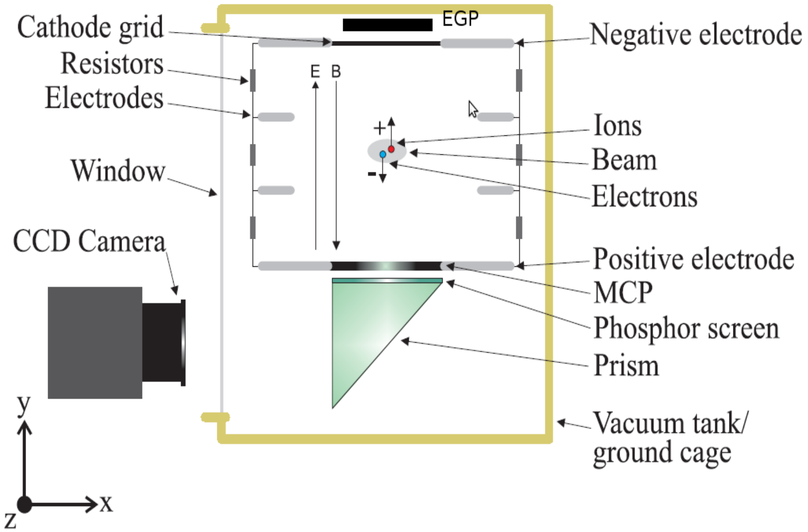


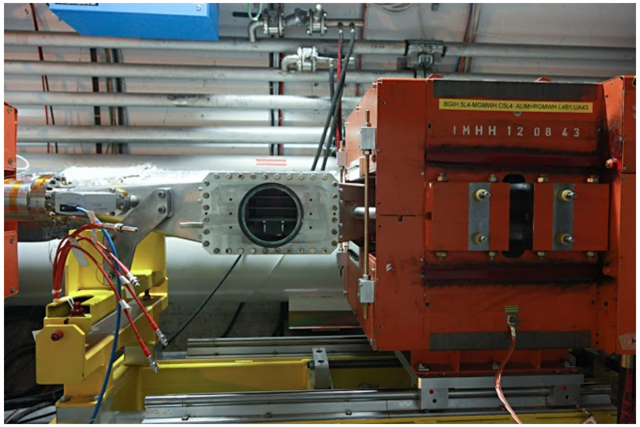


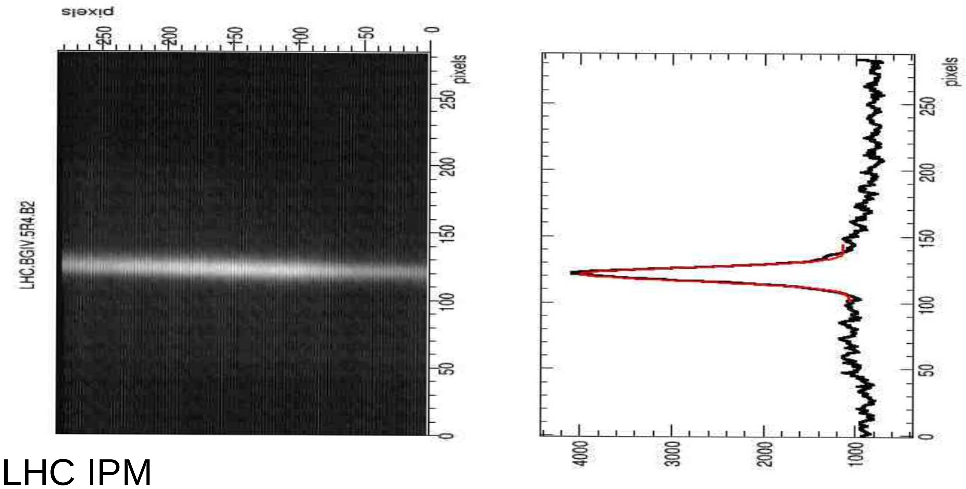
IPM concept

Ionization Profile Monitor (IPM):

- Measures transverse profile of particle beam.
- Rest gas (pressure 10^{-8} mbar) is ionized by the beam.
- Electric field is used to transport electrons/ions to a detector.
- If electrons are used – additional magnetic field is usually applied to confine their movement.







LHC IPM

Variations of IPMs

Technical decision	Pros	Cons
Electron collecting	speed (electrons need <5 ns to reach detector), no space-charge effect from other bunches	usually need magnets (expensive)
Detector: MCP+optical readout	theoretical resolution down to about 100 µm (difficult in practice), 2D image	cameras can do ~60 fps (slow!)
Detector: MCP+anode strip readout	fast readout (kHz)	resolution about 500 µm RF coupling to beam fields
Detectors: MCP+resistive anode	cheap readout (1 channel), resolution down to 300 µm, 2D image(!)	pileup issue (100 kHz max rate to register particles)
Detector: Channeltron(s)	simple, less sensitive to dynamic effects than MCP	resolution > 6 mm
Detector: Hybrid Silicon Pixel	resolution < 50 µm, electron energy measurement, no MCP	need in-vacuum cooling, advanced readout electronics

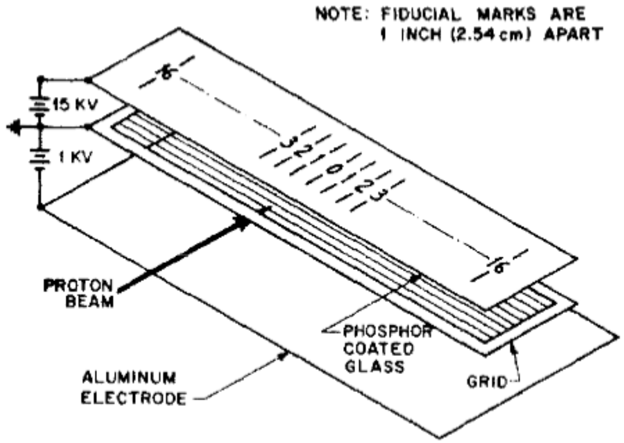
Not a complete list...

Some examples

- First IPM: F. Hornsta, Argonne, 1967

  (no MCP)

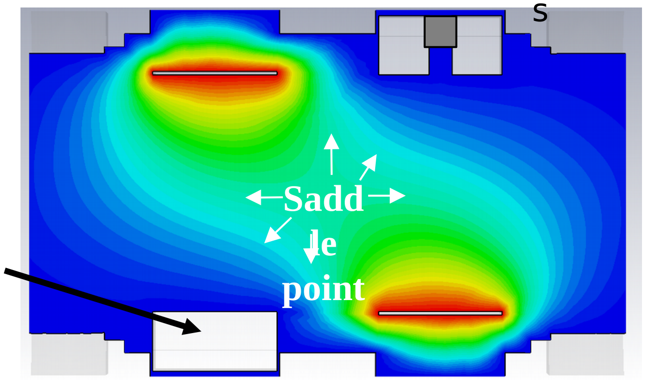
F. Hornstra, Jr. and W. H. DeLuca, Proceedings of the Sixth International Conference on High Energy Accelerators p. 374 (1967).



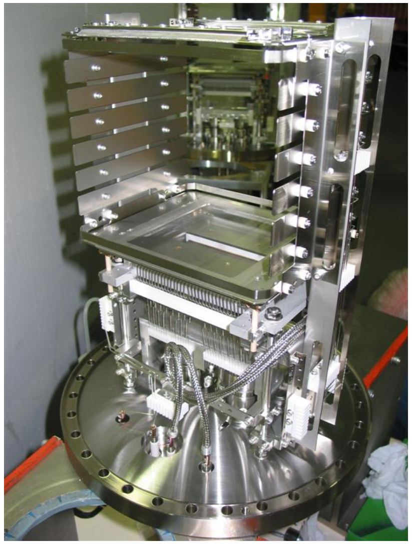
- GSI IPMs:
  - 4 types, optical and electrical readout
- Exotic: ISIS system
  - Detectors not build-into electrodes

MCPM Detectors

SCPM Detector



Longitudinal electric potential distribution created by the two drift field electrodes



Coutesy T. Giacomini

Typical issues

- Electron background – electrons drifting into detector, issues often difficult to understand (see spare slides: J-PARC, ISIS examples)
- Profile deformation due to electrons/ions interaction with bunch charges
- Dynamic effects on MCP – if bunch generates lot of electrons in short time, it depletes MCP
- MCP/Phosphor response nonuniformity
- ...

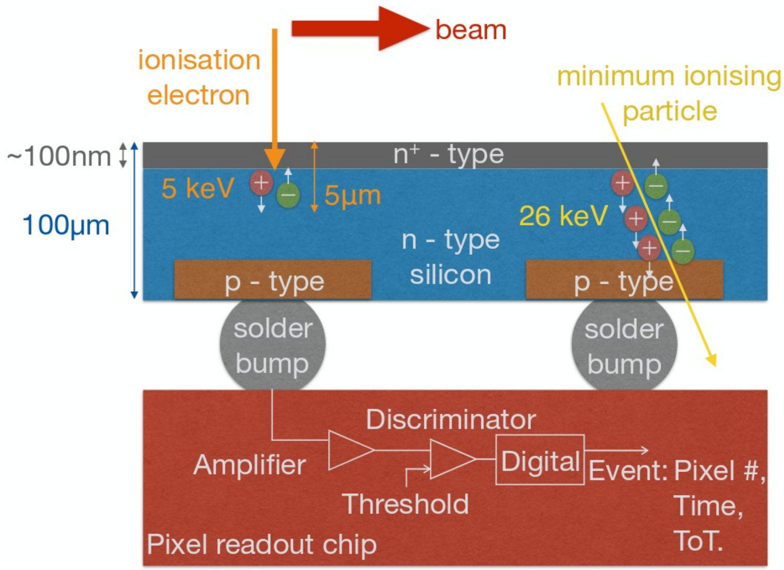
Issues are usually related to small, high intensity beams.

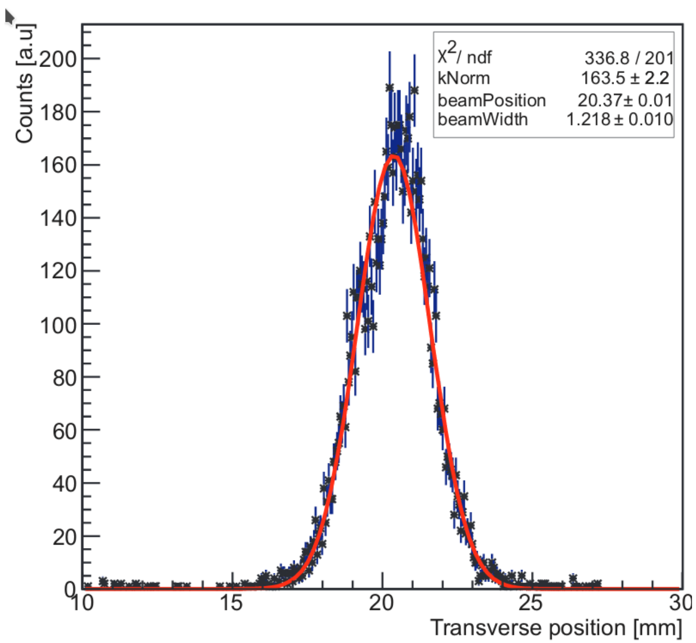
In many machines IPMs work very reliable and provide accurate measurements.

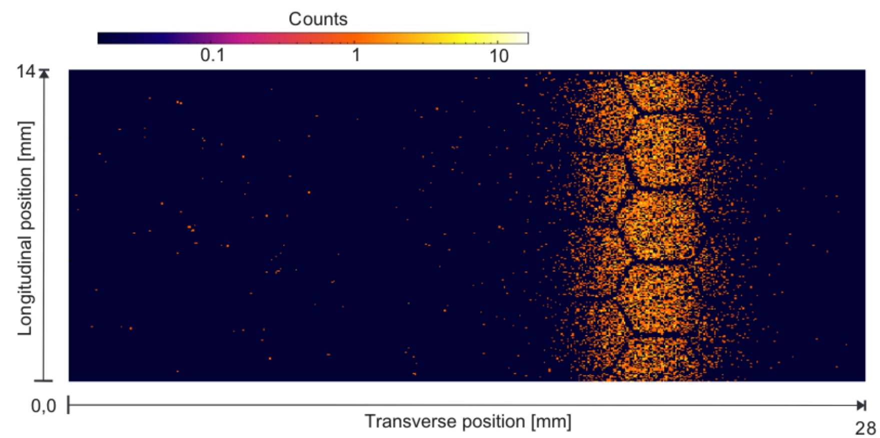
Hybrid Pixel detector readout

- Novel readout technique – here using Timepix3
- Developed to get rid of MCP
- Information: pixel position, timestamp

  (resolution: 1.625 ns) and energy estimation (ToT)
- But it has another advantage: 55x55 μm[2] pixels
- Prototype constructed, currently operated in CPS



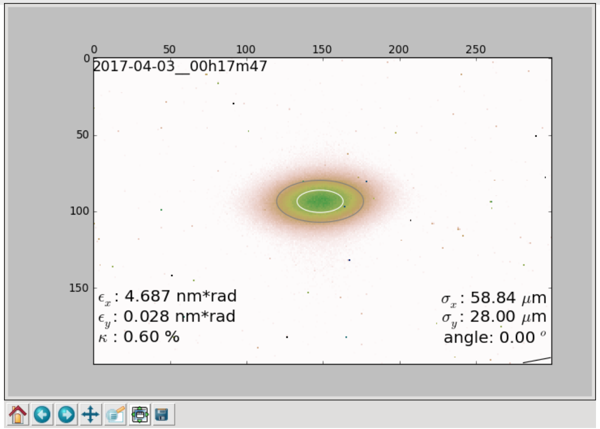


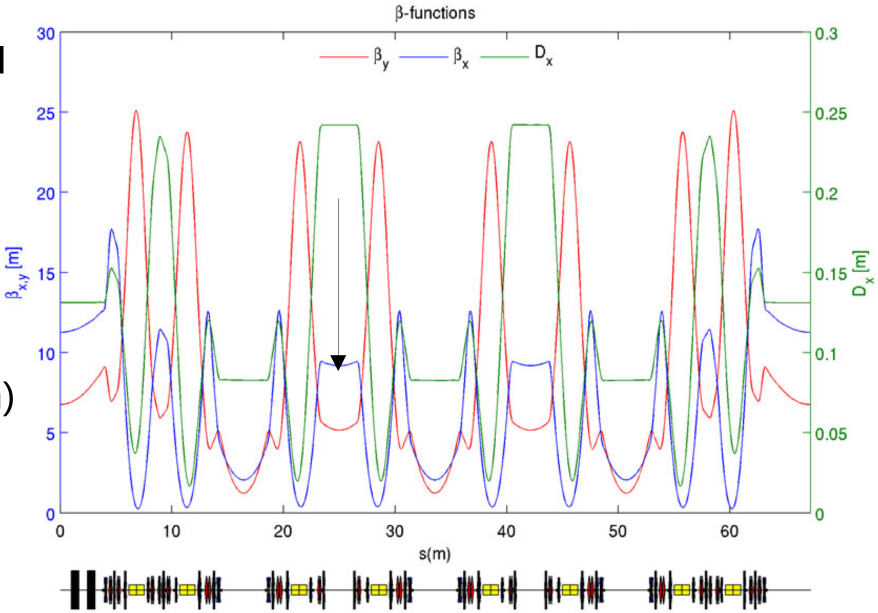


J. Storey et al., Proc. IBIC 2017(WEPCC07)

IPM for light sources?

- Example: ALBA, emittance (H): 4.3 nm*rad, β_x= 10 m, energy= 3 GeV, dE/E=10^{-3}
  beam size = 288 µm
- Vertical emittance: 0.03 nm*rad, β_y= 20 m,
  beam size=25 µm
- Good news:
  - 280 µm could be measured using MCP+optical readout or better using Hybrid Silicon Pixel readout (5 points/σ)
  - CLICpix (under development) has 25 µm pixel size – theoretical resolution
    25/√12 = 7 µm, rel. error=0.3% (2% for 55 µm)





$$\mu_\sigma = \left.\frac{\sigma_{measured}-\sigma_{beam}}{\sigma_{beam}}\right|_{systematic} = \frac{\sqrt{\sigma_{beam}^2+\sigma_{pixel}^2}-\sigma_{beam}}{\sigma_{beam}} =$$

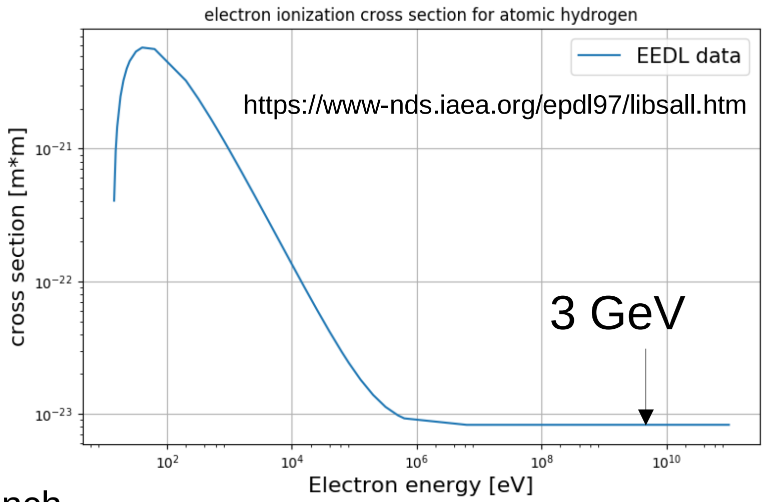
$$= \frac{1}{\sigma_{beam}}\sqrt{\left(\sigma_{beam}^2+\frac{d^2}{12}\right)}-1 = \sqrt{1+\frac{1}{12\eta^2}}-1$$

F. Roncarolo, PhD thesis

Plots courtesy N. Ayala

IPM for light sources – ionization yield

- Bunch charge 2×10^{9} electrons
- Cross-section: 8.3×10^{-24} m^2
- Gas pressure: 10^{-9} mbar
- Detector length: 1.4 cm (single Timepix3)
- Result: $\lesssim$ 1 ionization/bunch
- Conclusions:
  - per-turn measurement possible
  - need several hundred turns to do bunch-per-bunch



Remark: H_2 threshold ionization energy is 15.4 eV.

Synchrotron radiation from your main dipoles have critical energy of 8.5 keV – make sure it does not contribute to beam profile measurement.

Digression:
first IPM for electron machine

TUPC088 Proceedings of IPAC2011, San Sebastián, Spain

AN IONIZATION PROFILE MONITOR FOR THE DETERMINATION OF THE FLASH AND PITZ BEAM PARAMETER

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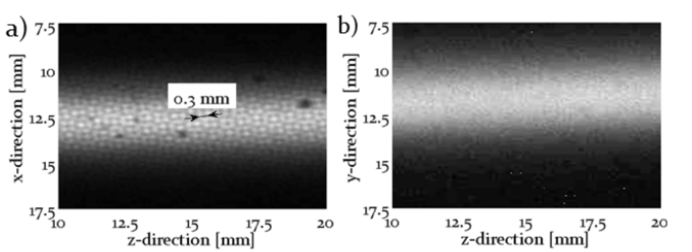


Figure 3: Recorded images of one particular photon beam; a) grid-IPM, b) box-IPM.

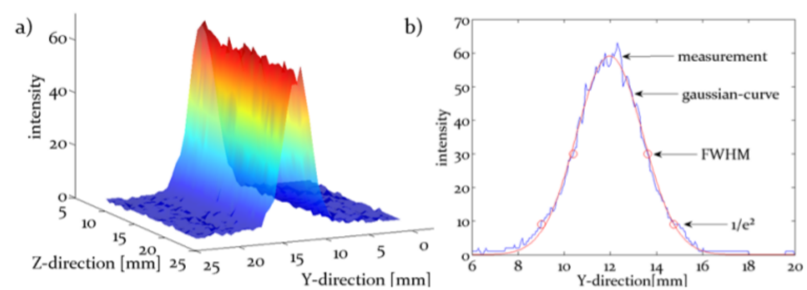


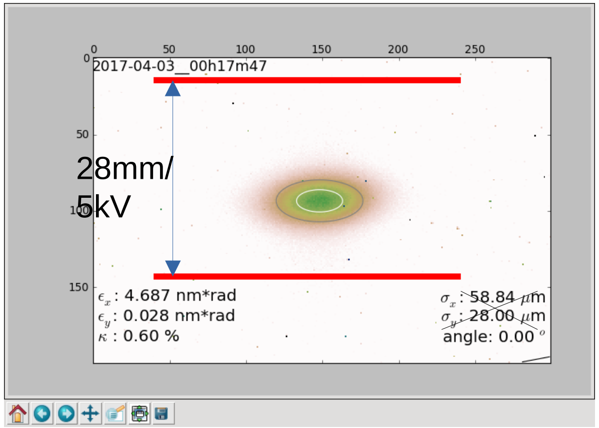
Figure 4: Beam at FLASH; a) 3D-profile, b) y-profile.

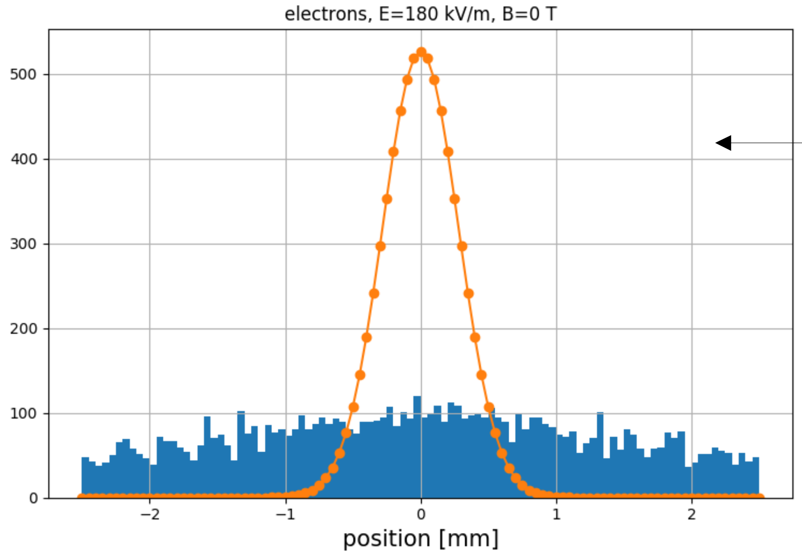
Soft X-ray

IPM for light sources – scenarios (I)

- β_x= 9 m, β_y= 5 m
- Beam sizes: σ_x=280 µm, σ_y=12 µm, σ_z=18 ps
- Bunch spacing 2 ns

Scenario 1: E=180 kV/m, B=0 T, electrons





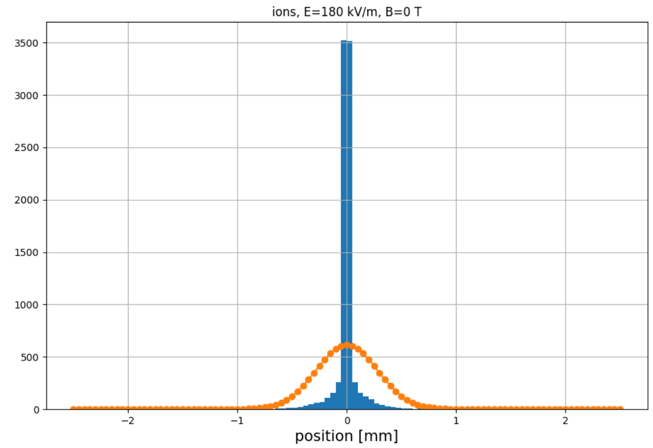
Using Virtual-IPM – python package, see D. Vilsmeier, presentation at http://indico.gsi.de/event/IPM17
"A Modular Application for IPM Simulations", Proc. of IBIC17 (WEPCC07)
(zero initial velocities)

Maybe ions work?
Or we must add magnetic field!

IPM for light sources – scenarios (II)

Scenario 2:

E=180 kV/m, B=0.2 T, ions (H^+)

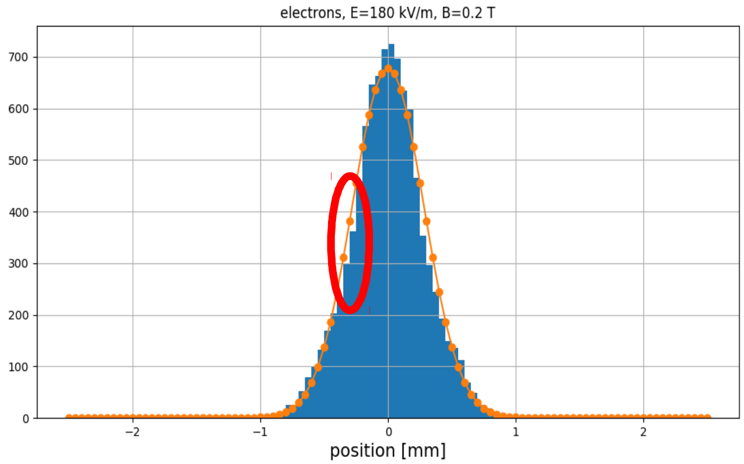


Ions move too slowly (200 ns to reach the detector) – they interact with several subsequent bunches

very large distortion

Scenario 3:

E=180 kV/m, B=0.2 T, electrons

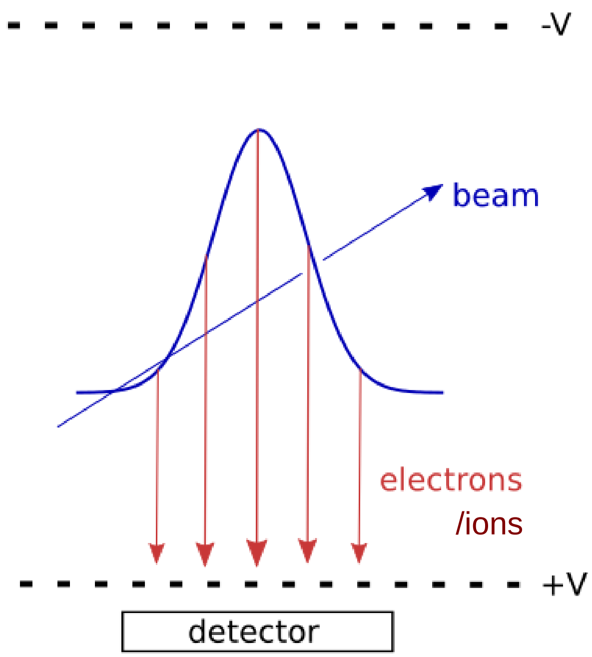


Some deviation visible, gauss fit gives 285 μm

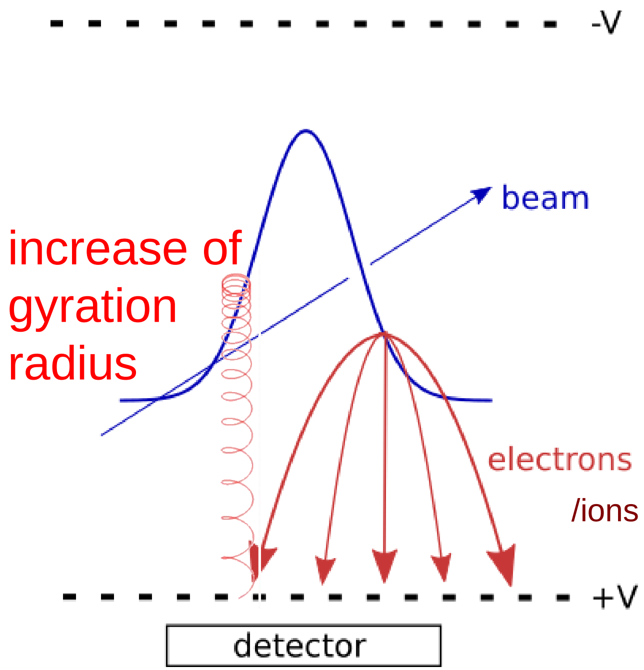
small distortion, can be corrected?

Profile distortion in IPM - source

- Ideal case
- Particles are moving on straight lines towards the detector



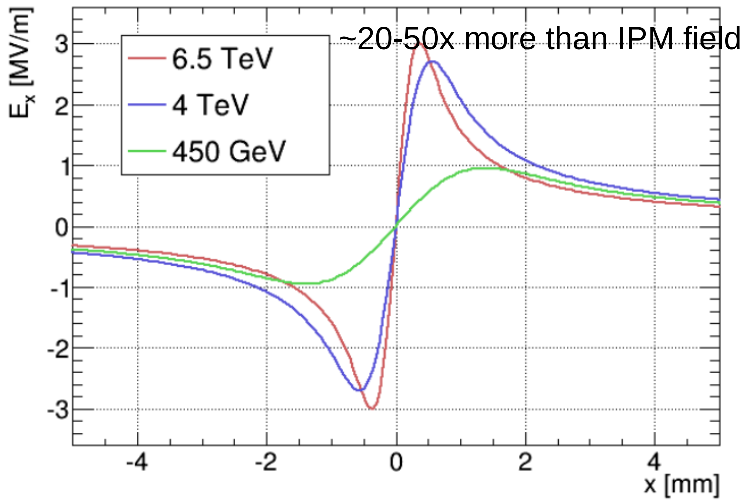
- Real case
- Particle trajectories are influenced by initial momenta and by the interaction with the beam field

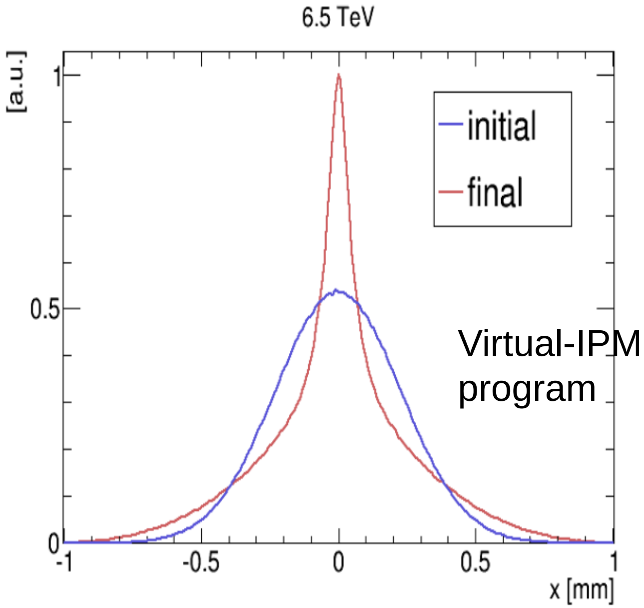


… instrumental effects such as camera tilt, optical point-spread-functions, point-spread functions due to optical system and multi-channel plate granularity etc, etc… come on top!

Profile distortion in IPM – simulation for LHC case

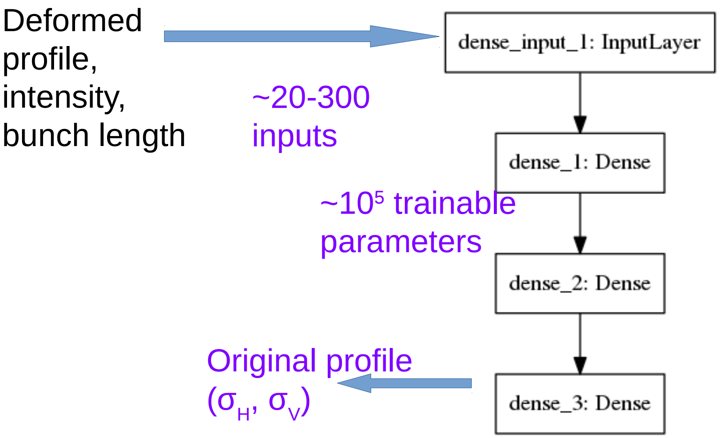
- Distortion occurs for large beam fields ↔ large charge densities, large beam energies.
- Can be simulated with reasonable assumptions.
- No simple mathematical correction procedure exists (especially for case with B-field)
- Ideas: using higher B-field, use sieve to select electrons according to gyroradius, etc...



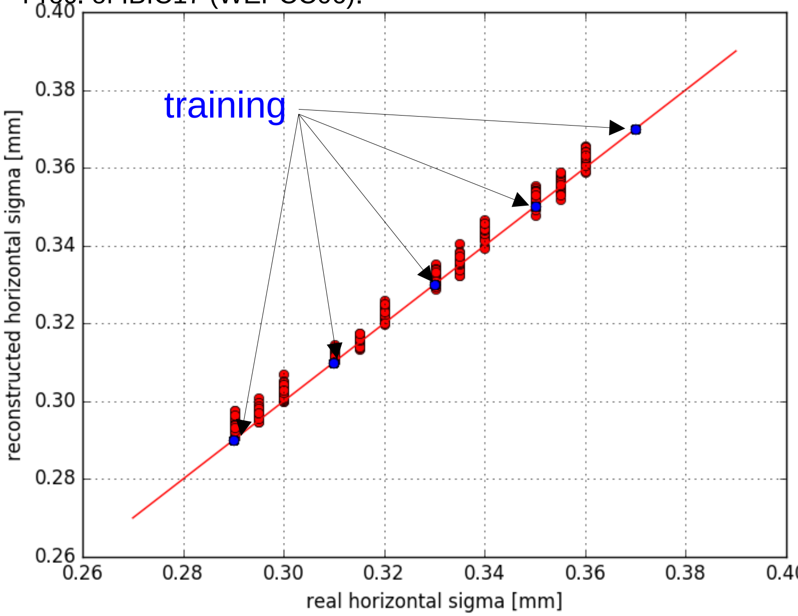


Exercise: use Neural Network

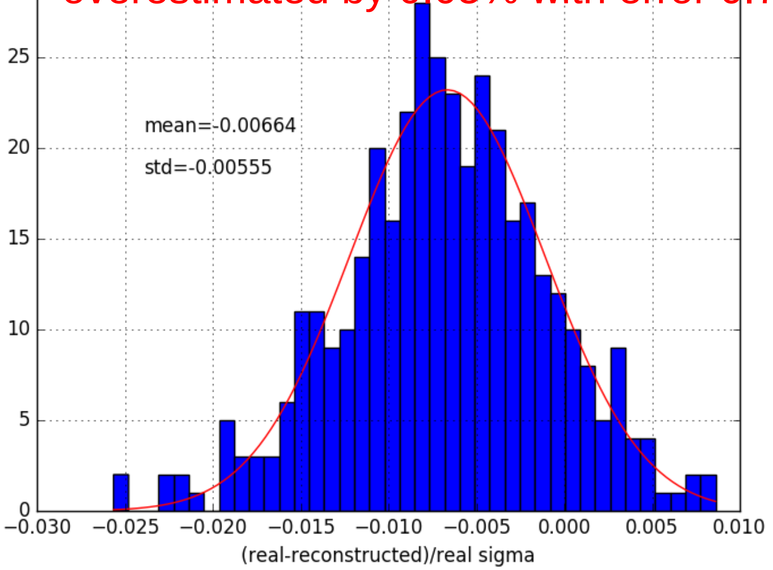
- tensorflow+keras: very simple to use
- non-linear multivariate problem – ideal for NN
- training and validation on simulation
- error is small but difficult to estimate



R. Singh, et al., Simulation supported profile reconstruction with machine learning, Proc. of IBIC17 (WEPCC06).



Beam sigma systematically overestimated by 0.05% with error 0.7%



Conclusions

- IPMs are standard devices to measure emittance in hadron machines (synchrotrons, cyclotrons, sometimes also transfer lines and linacs).
- Recent application of Hybrid Pixel Detectors allow to improve spatial resolution by factor ~5.
- This opens a possibility to use them in light sources like ALBA.
- Eventual measurement error due to beam space charge can be significantly reduced using Machine Learning technique.

Acknowledgments: D. Vilsmeier, A. Reiter, P. Forck, R. Singh, J. Storey, K. Sato ...