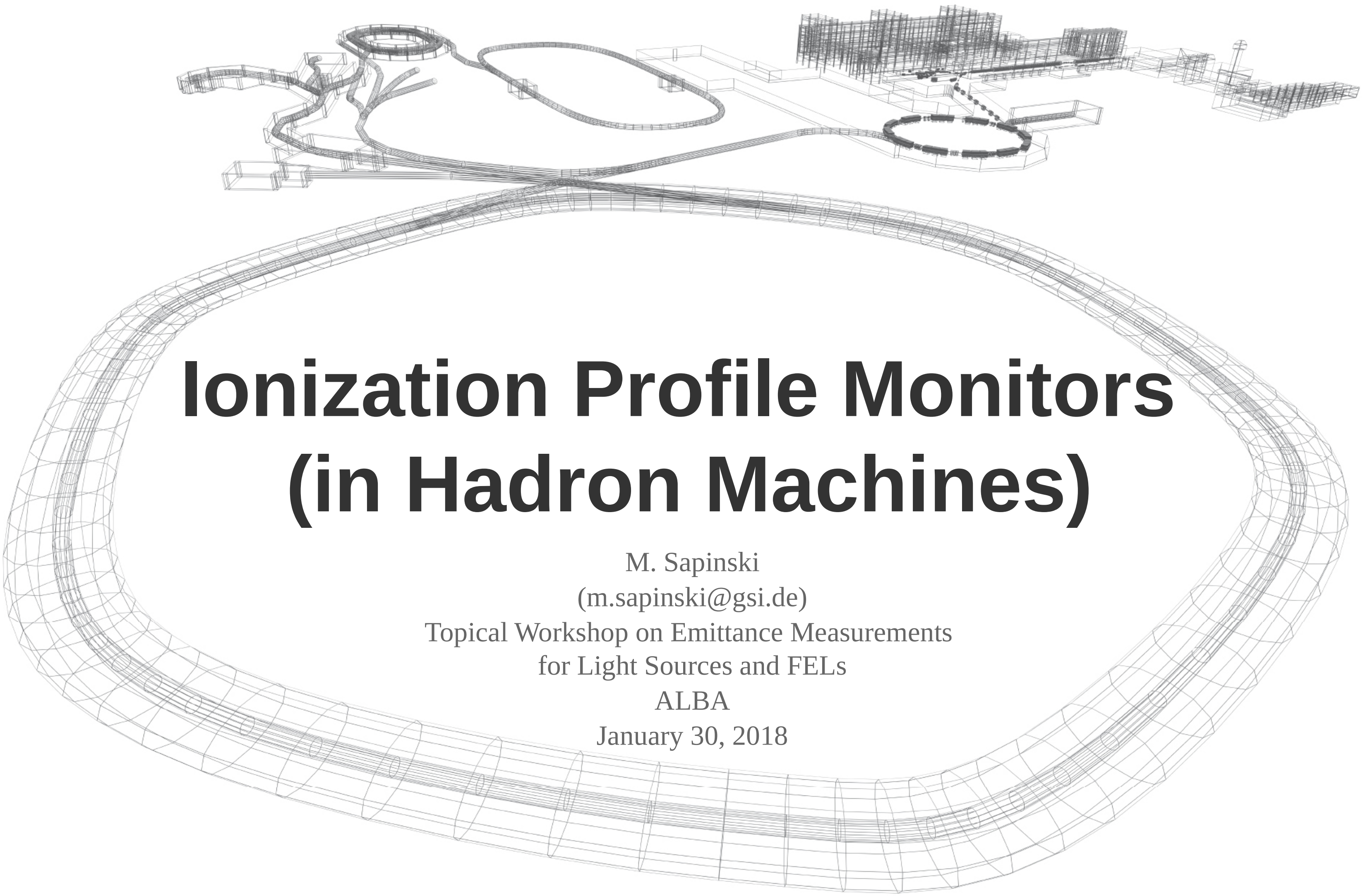

Ionization Profile Monitors (in Hadron Machines)

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

Light source in FAIR?

Light source in FAIR?

January 18, 2018

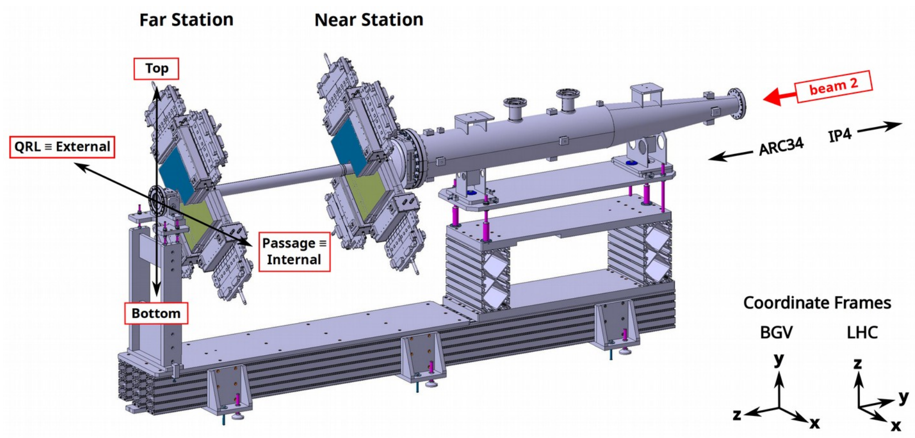
Report on recent developments in Ionization Profile Monitors which maybe of use for electron machines

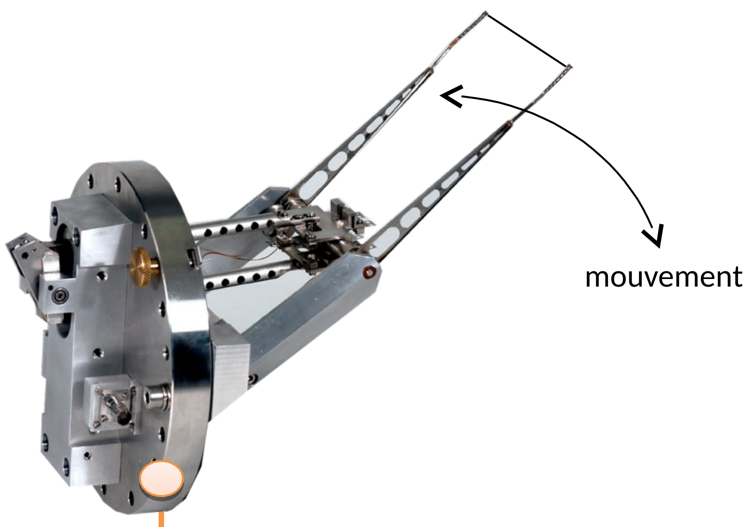
Outline

- 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

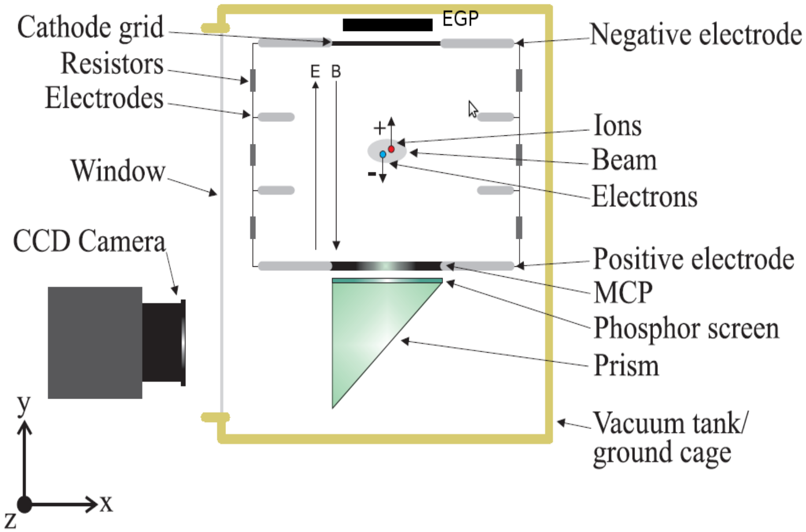


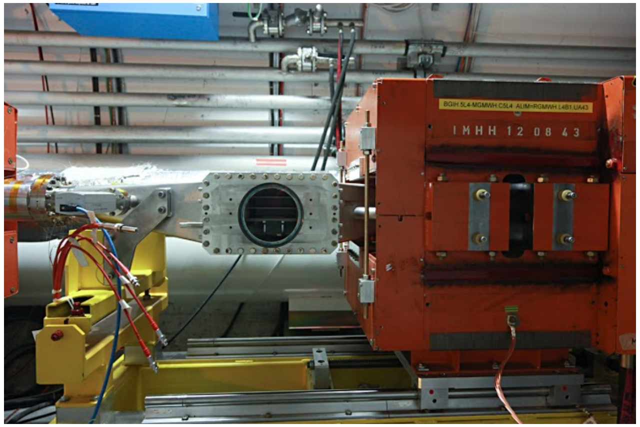


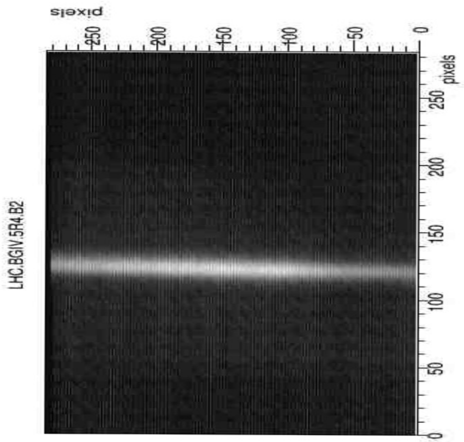
IPM concept

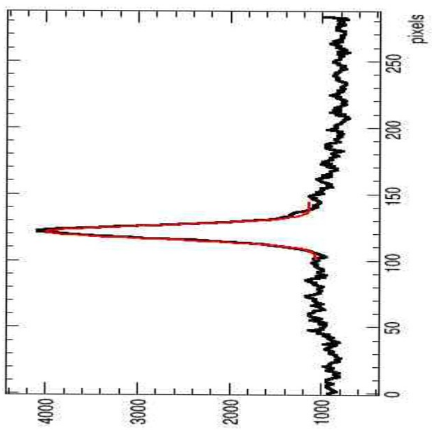
Ionization Profile Monitor (IPM):

- 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

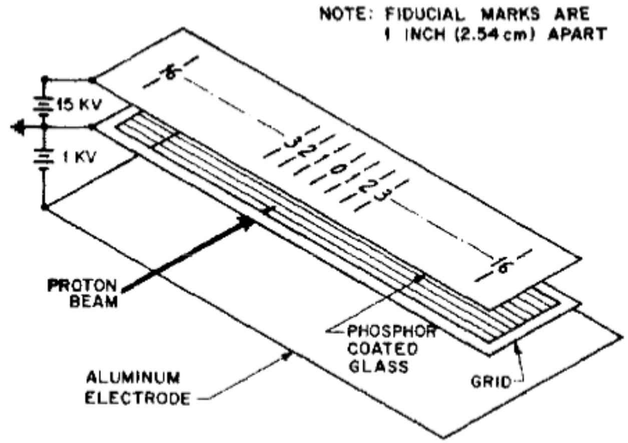
Not a complete list...

Some examples

- First IPM: F. Hornsta, Argonne, 1967

  (no MCP)

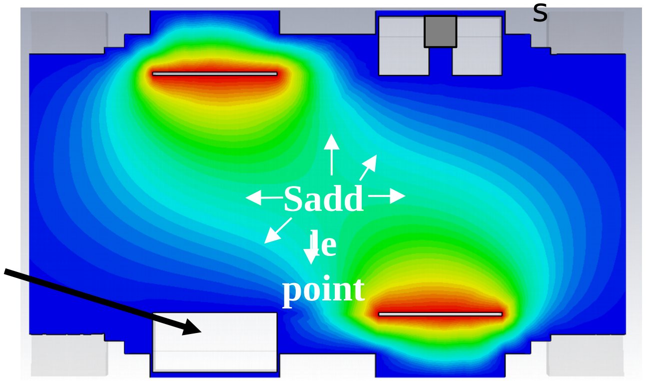
F. Hornstra, Jr. and W. H. DeLuca, Proceedings of the Sixth International Conference on High Energy Accelerators p. 374 (1967).



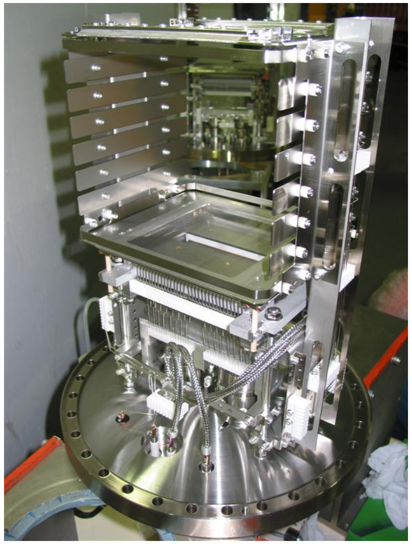
- GSI IPMs:
  - 4 types, optical and electrical readout
- Exotic: ISIS system
  - Detectors not build-into electrodes

MCPM Detectors

SCPM Detector



Longitudinal electric potential distribution created by the two drift field electrodes



Coutesy T. Giacomini

Typical issues

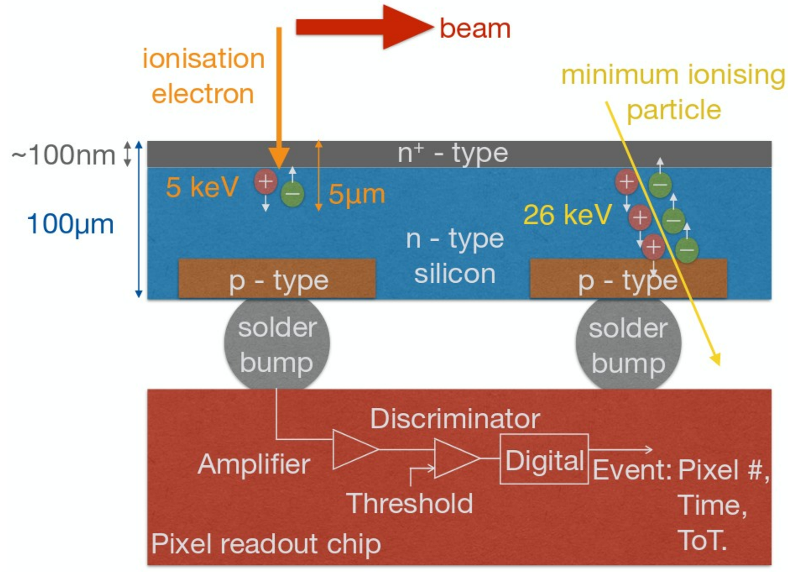
- Electron background – electrons drifting into detector, issues often difficult to understand (see spare slides: J-PARC, ISIS examples)
- Profile deformation due to electrons/ions interaction with bunch charges
- Dynamic effects on MCP – if bunch generates lot of electrons in short time, it depletes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

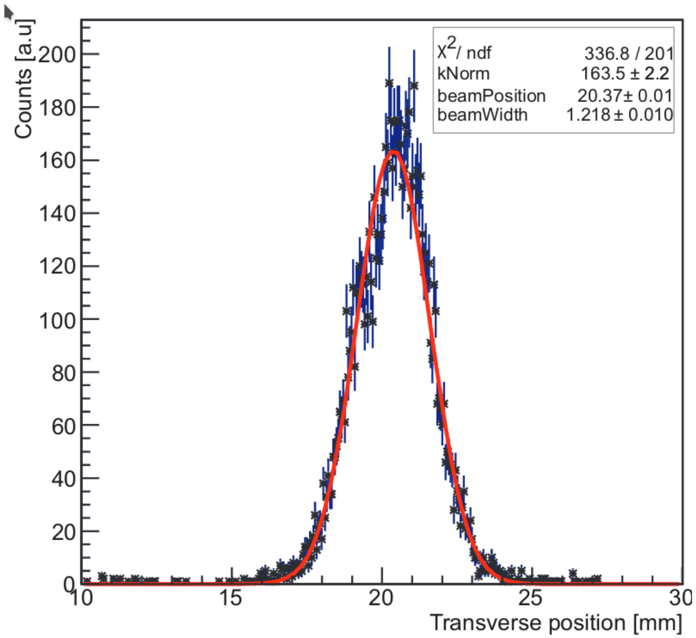
Issues are usually related to small, high intensity beams.

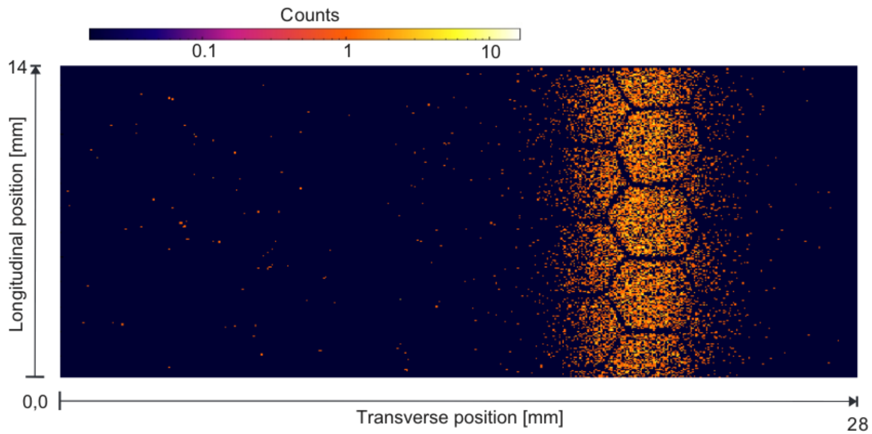
In many machines IPMs work very reliable and provide accurate measurements.

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 μm² pixels
- Prototype constructed, currently operated in CPS



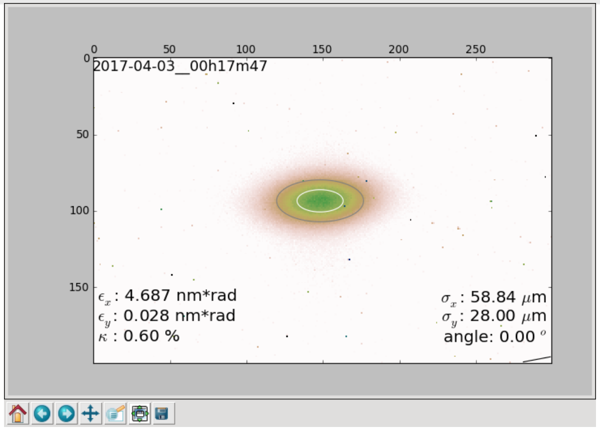




J. Storey et al., Proc. IBIC 2017(WEPCC07)

IPM for light sources?

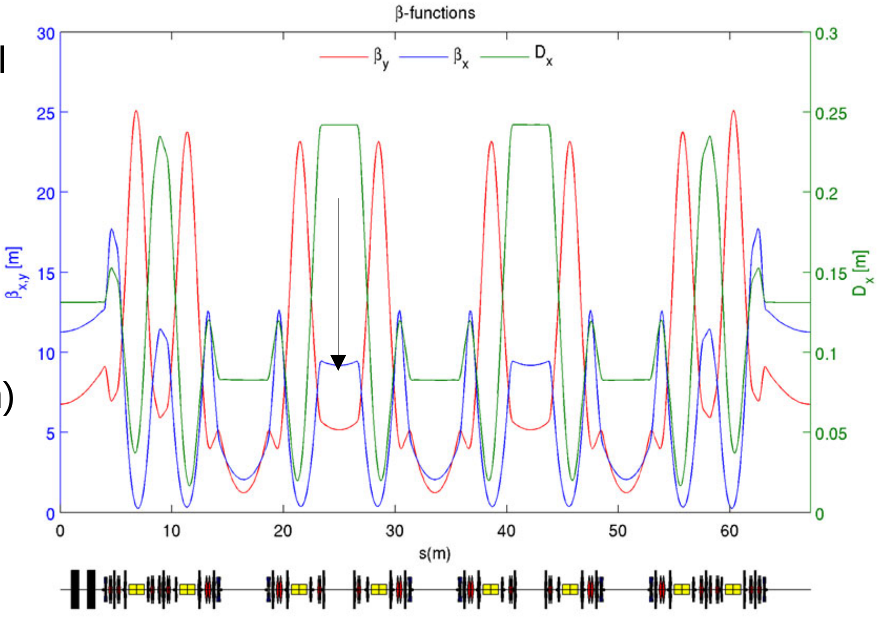
- Example: ALBA, emittance (H): 4.3 nm*rad, β_x= 10 m, energy= 3 GeV, dE/E=10^{-3}
  beam size = 288 µm
- Vertical emittance: 0.03 nm*rad, β_y= 20 m, beam size=25 µm
- Good news:
  - 280 µm could be measured using MCP+optical readout or better using Hybrid Silicon Pixel readout (5 points/σ)
  - CLICpix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



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

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

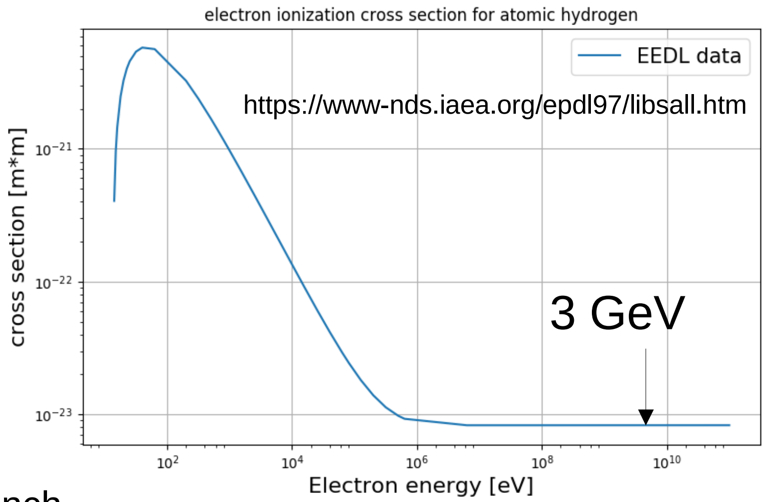
F. Roncarolo, PhD thesis



Plots courtesy N. Ayala

IPM for light sources – ionization yield

- Bunch charge 2x10^{9} electrons
- Cross-section: 8.3x10^{-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

J.Mießner*, H.-J.Grabosch, R.Sternberger, M.Markert, DESY, 15738 Zeuthen, Germany
K.Tiedtke, DESY, 22603 Hamburg, Germany,
A.Hofmann, KIT, 76131 Karlsruhe, Germany.

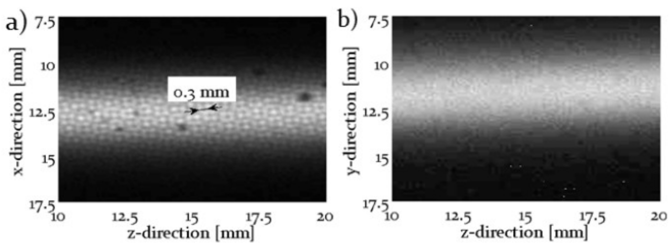


Figure 3: Recorded images of one particular photon beam; a) grid-IPM, b) box-IPM.

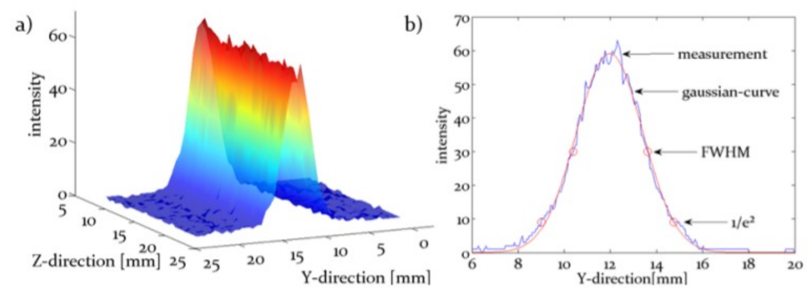
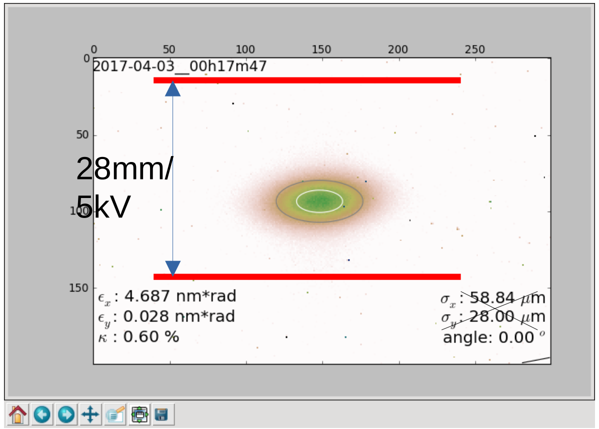


Figure 4: Beam at FLASH; a) 3D-profile, b) y-profile.

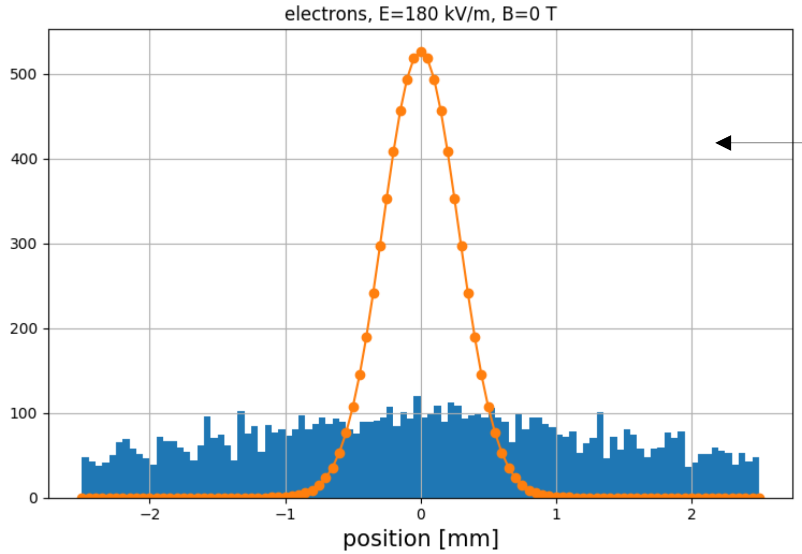
Soft X-ray

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



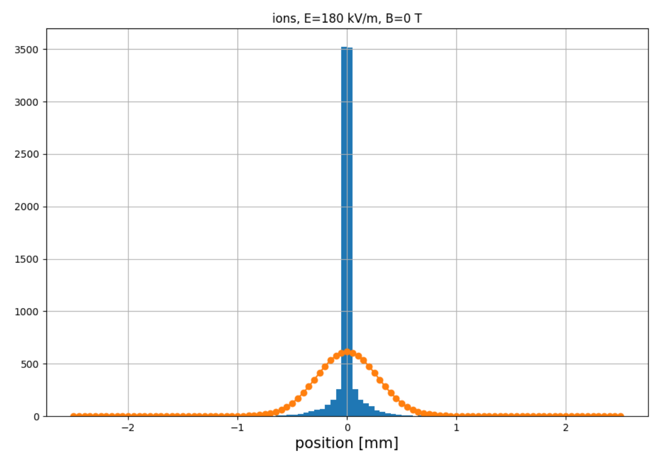
Using Virtual-IPM – python package, see D. Vilsmeier, presentation at http://indico.gsi.de/event/IPM17
"A Modular Application for IPM Simulations", Proc. of IBIC17 (WEPCC07)
(zero initial velocities)

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^+)

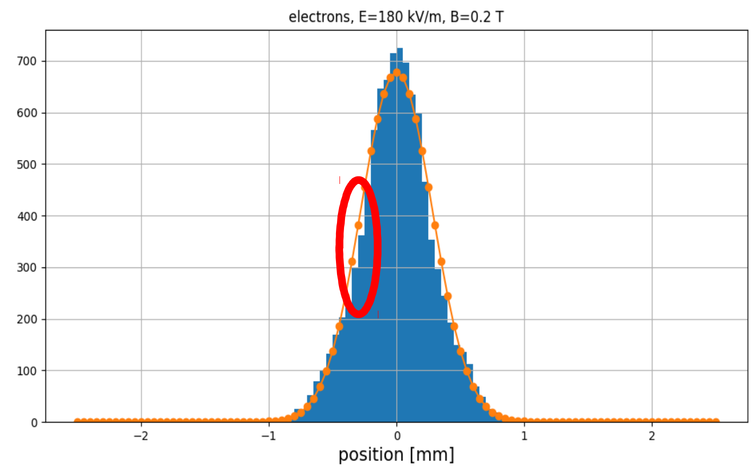


Ions move too slowly (200 ns to reach the detector) – they interact with several subsequent bunches

very large distortion

Scenario 3:

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

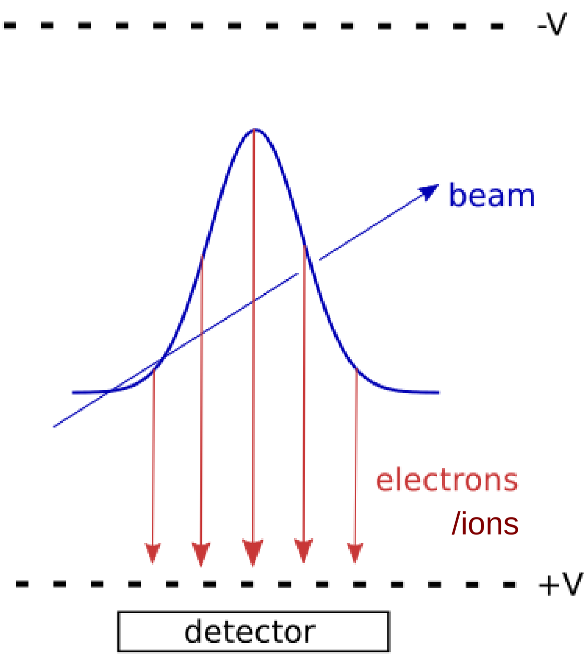


Some deviation visible, gauss fit gives 285 μm

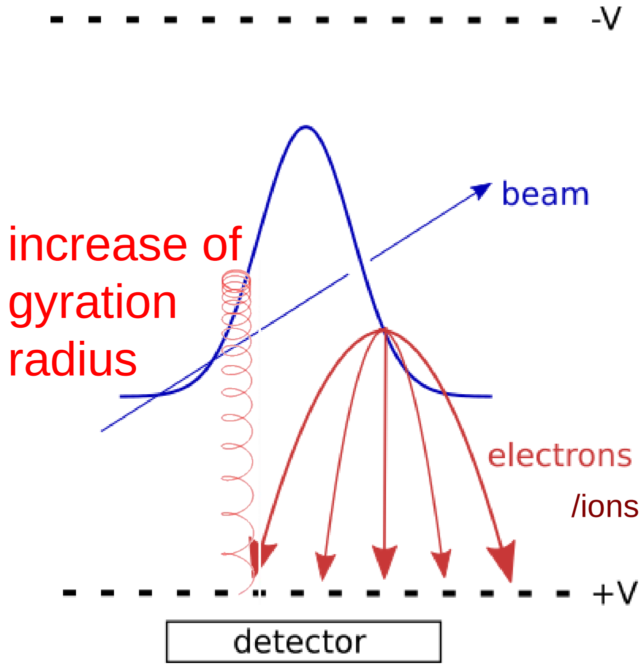
small distortion, can be corrected?

Profile distortion in IPM - source

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



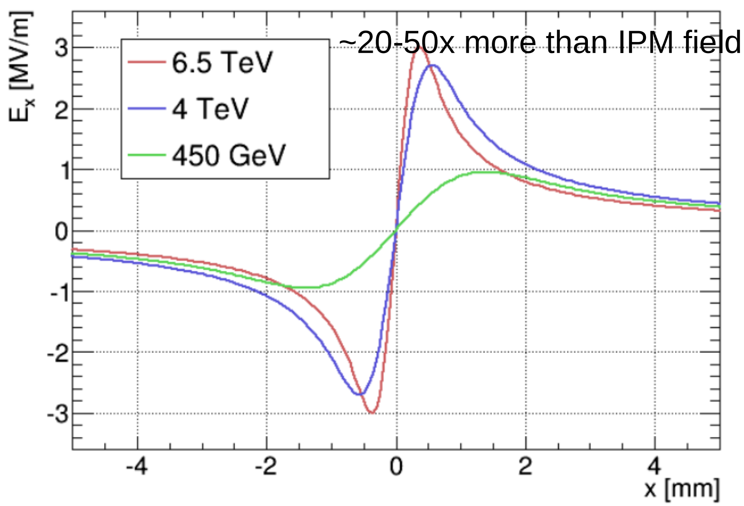
- Real case
- Particle trajectories are influenced by initial momenta and by the interaction with the beam field

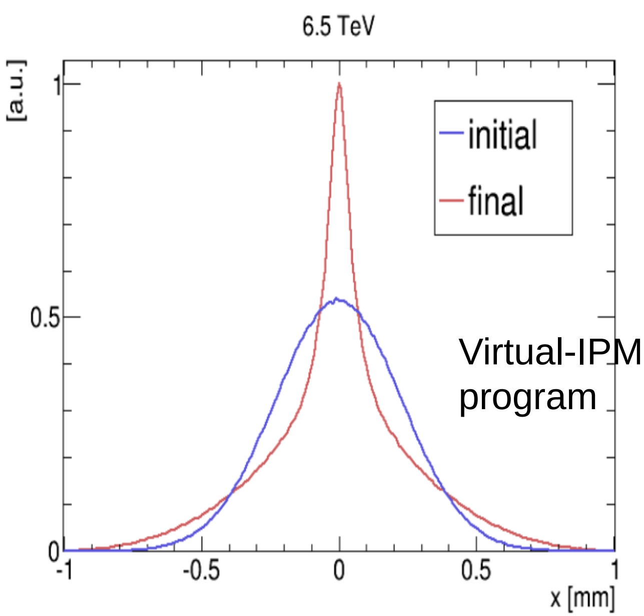


… instrumental effects such as camera tilt, optical point-spread-functions, point-spread functions due to optical system and multi-channel plate granularity etc, etc… come on top!

Profile distortion in IPM
– simulation for LHC case

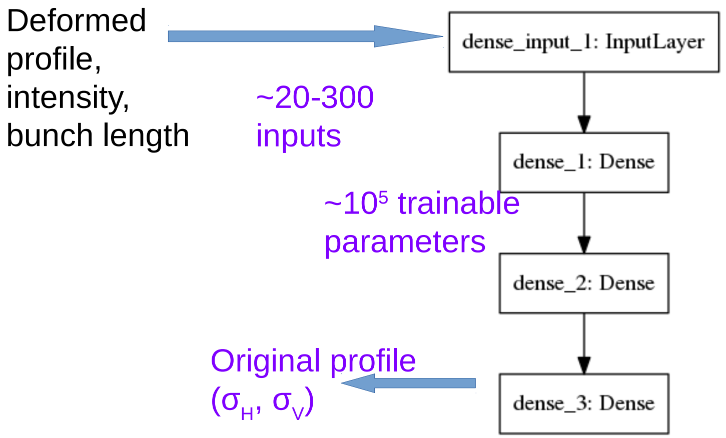
- Distortion occurs for large beam fields ↔ large charge densities, large beam energies.
- Can be simulated with reasonable assumptions.
- No simple mathematical correction procedure exists (especially for case with B-field)
- Ideas: using higher B-field, use sieve to select electrons according to gyroradius,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



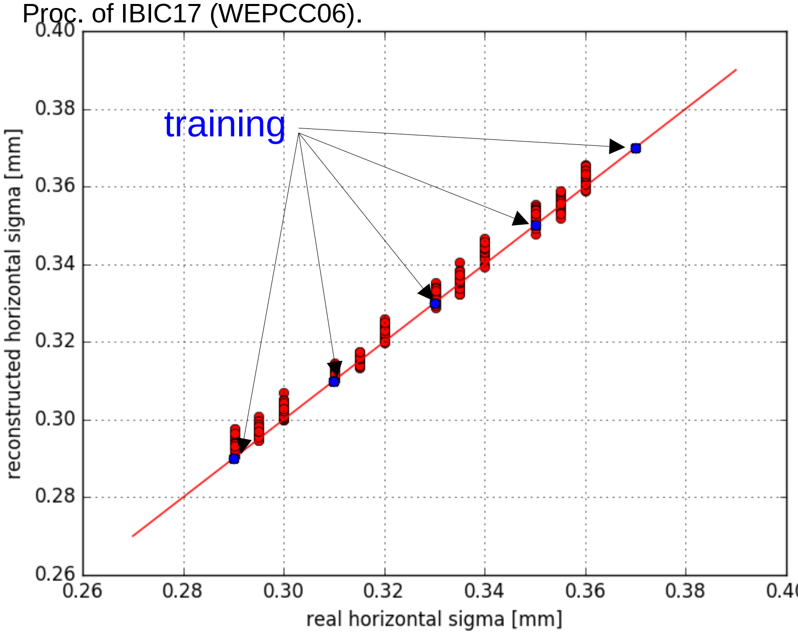


Exercise: use Neural Network

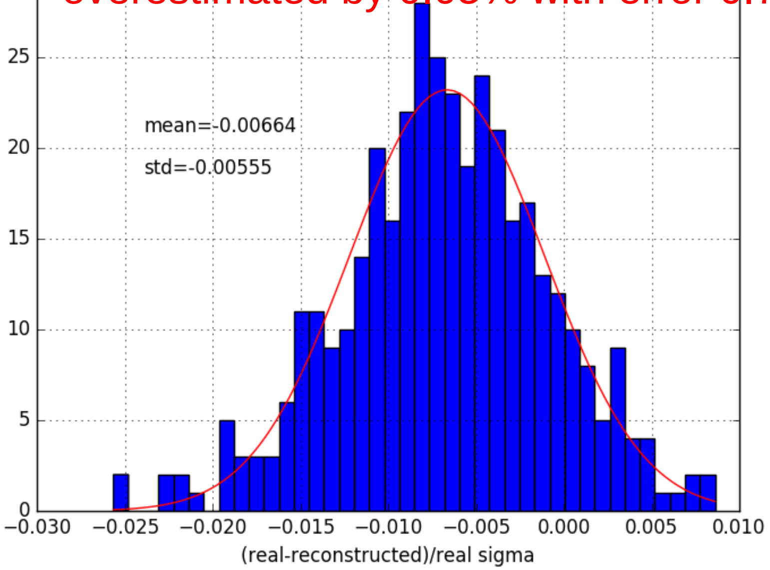
- tensorflow+keras: very simple to use
- non-linear multivariate problem – ideal for NN
- training and validation on simulation
- error is small but difficult to estimate



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.

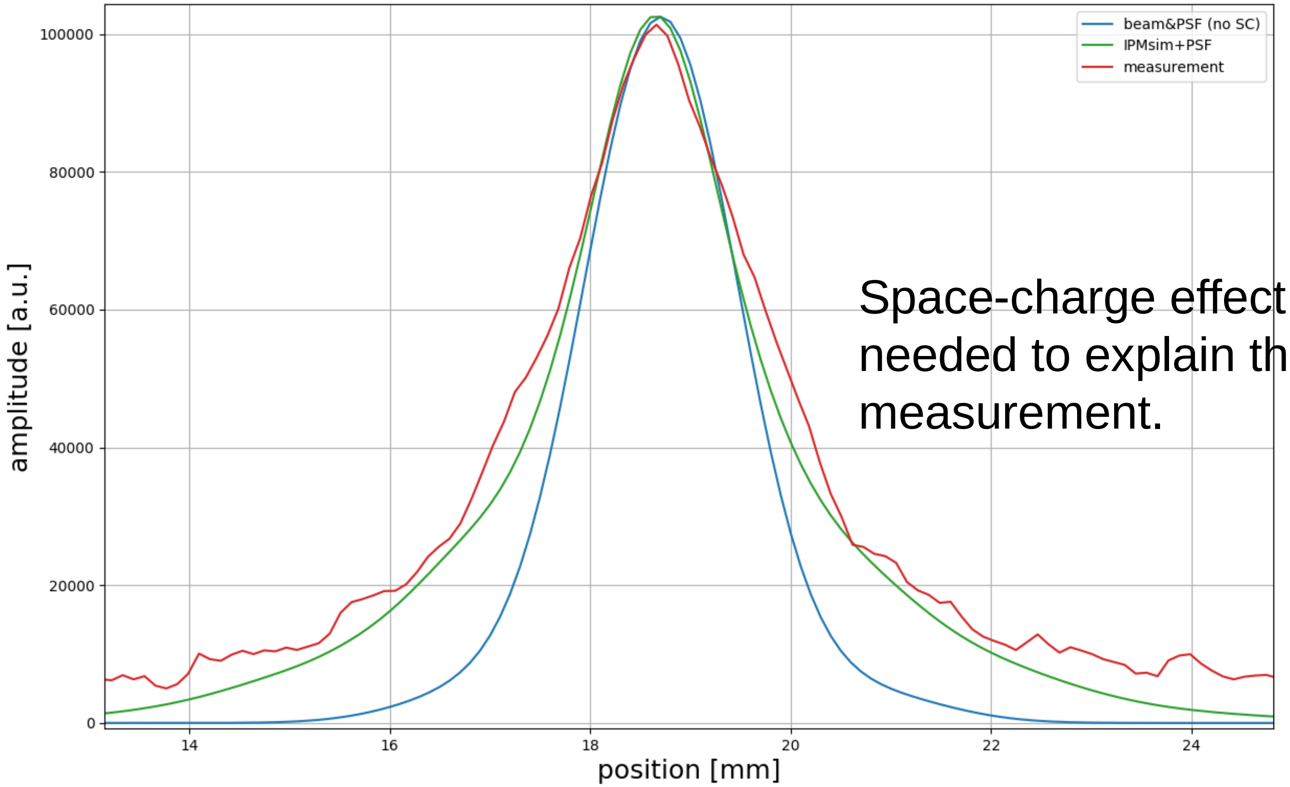
Acknowledgments: D. Vilsmeier, A. Reiter, P. Forck, R. Singh, J. Storey, K. Sato ...

Additional slides

Example 2:
IPM profile corrections

- No simple mathematical procedure exists.
- Using higher electric and magnetic fields (expensive, sometimes impractical).
- ➢ Electric and magnetic fields : Sieve method (deconvolve with PSF of radius of Gyration).
- ➢ *[Dominik Vilsmeier, Bachelor Thesis, CERN]*
- ➢ Electric fields only: Several calibration/correction attempts.
- ➢ Latest: Assumption on input beam distribution (Generalized Gaussian) and iterative procedure for input reconstruction from distorted profile using the data generated from simulation tool
- ➢ *[Jan Egberts, PhD Thesis, CEA Saclay]*

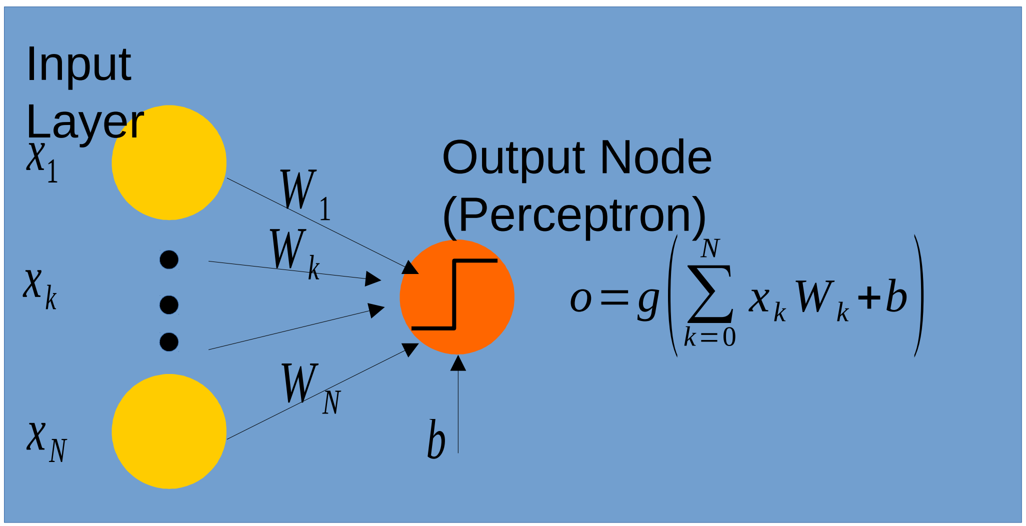
Space-charge on SPS beam

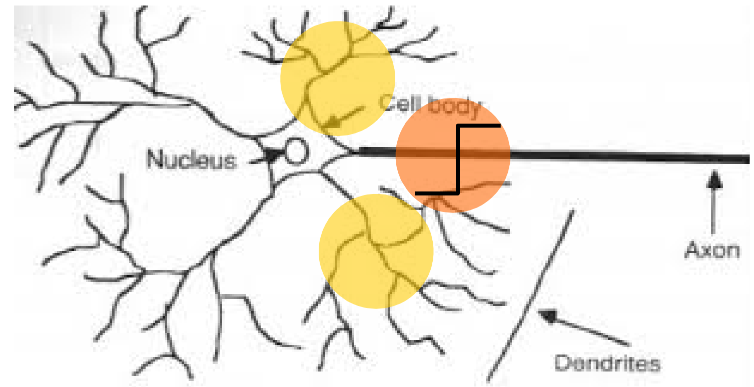


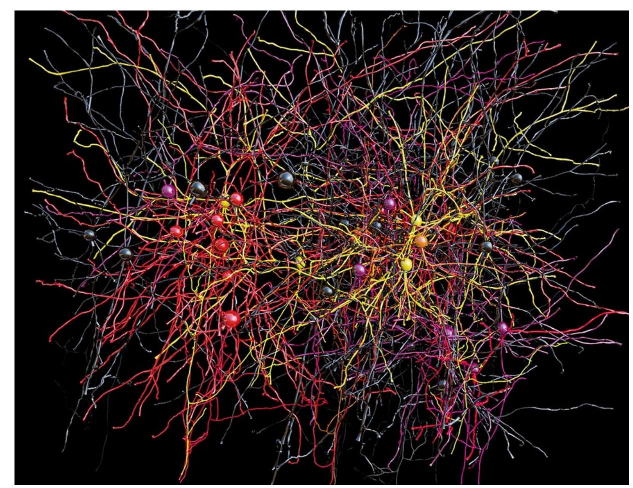
Space-charge effect clearly needed to explain this measurement.

Artificial Neural Network

- Biologically inspired → Brain cells -> neurons, computation via connections and thus Networks
- The basic node of ANNs is “Perceptron”





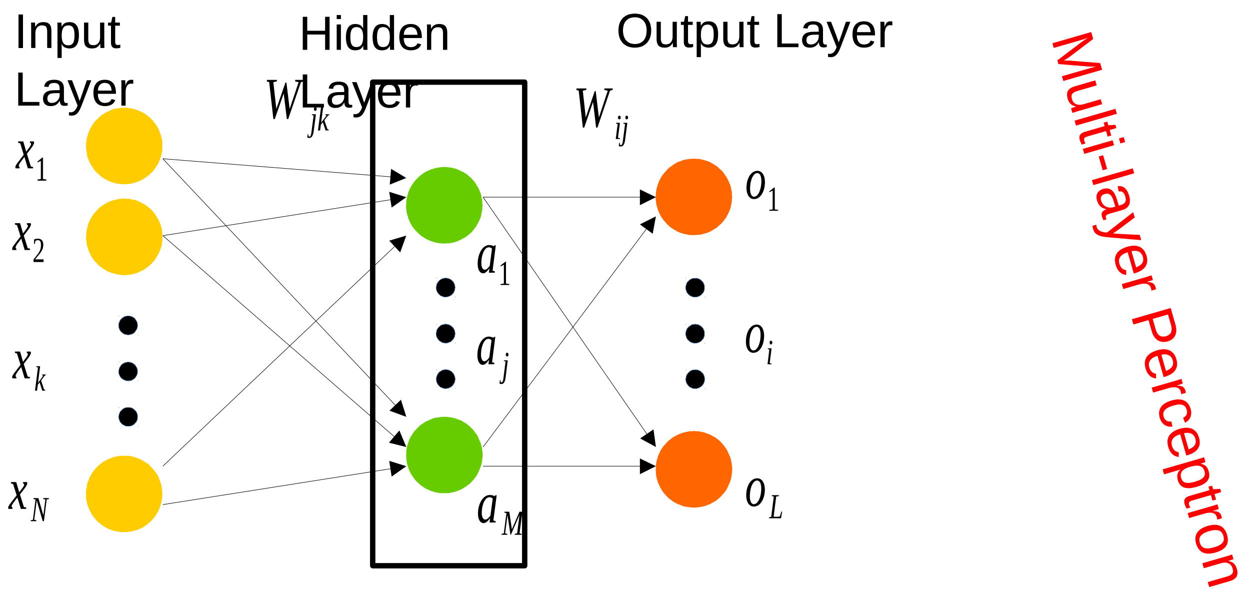


Perceptron parameters:

- Weights from the inputs (X) and bias (b)
- g is the activation function, a step-like function with a threshold

[https://www.wired.com/2016/03/took-neuroscientists-ten-years-map-tiny-slice-brain]

Hidden layers



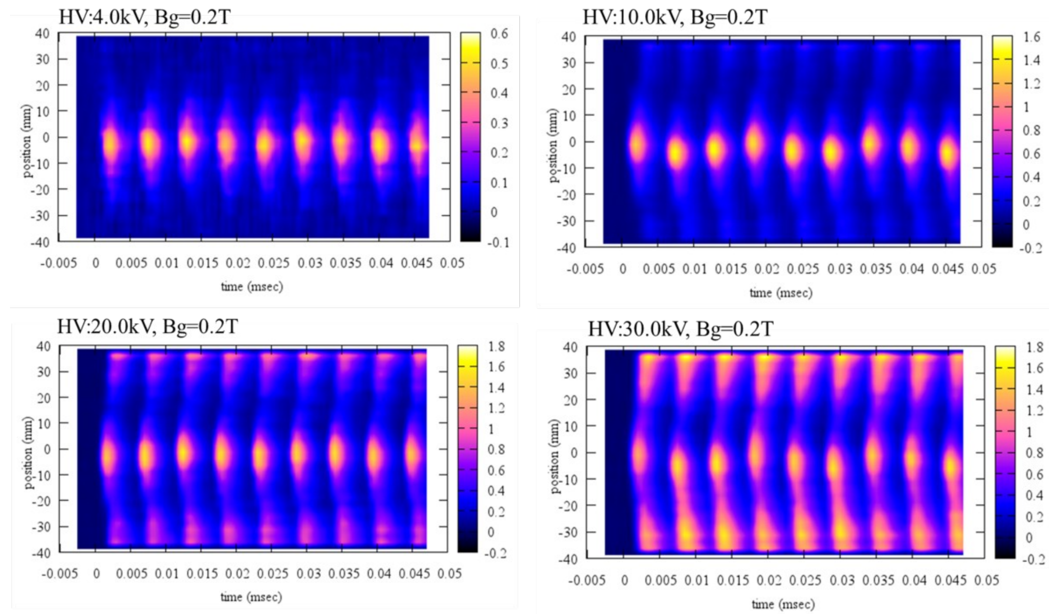
- Each hidden layer and output layer node is a perceptron

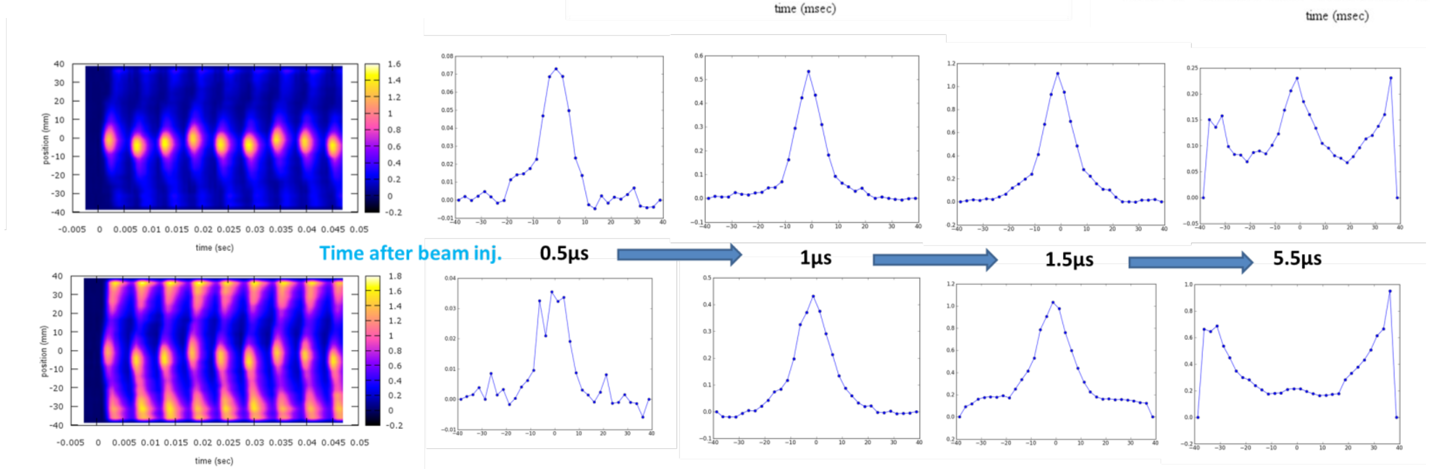
$$o_i = g\left(\sum_{j=0}^{M} W_{ij}\left(g\left(\sum_{k=0}^{N} x_k W_{jk} + b_j\right)\right) + b_i\right)$$

Adding "hidden" layer(s) allow non-linear target functions to be represented

Contamination issue : Electron collection with the magnetic field

- The turn by turn profile showed beam induced contamination, and it depends on HV
- The contaminant electrons appeared ~1.5 µs after the beam passage
- Mechanism of this contamination issue is under investigation

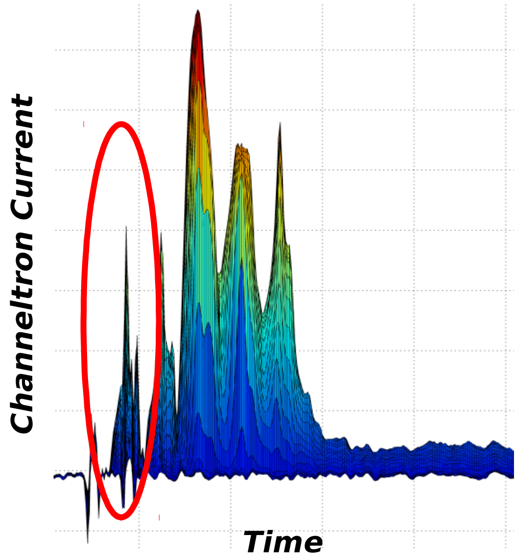




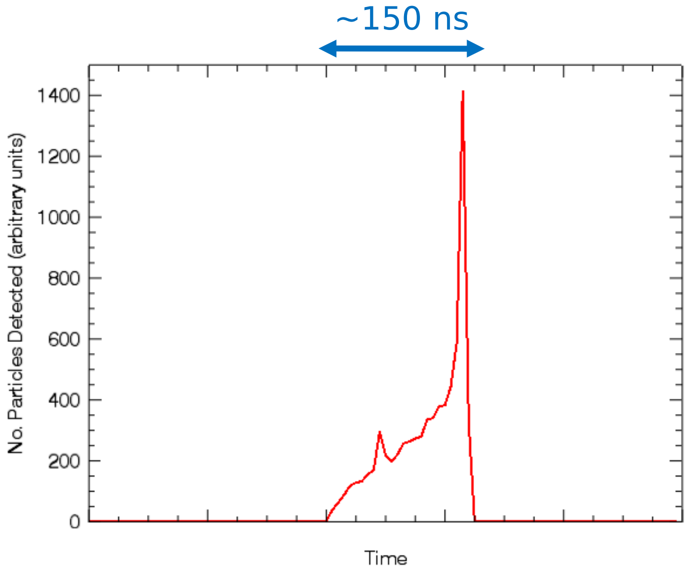
Sliced profile at selected time, 0.5, 1, 1.5, and 5.5 µs after the beam injection

Fast Amplifier Measurements: Multiple Time Peaks

- Time structure in simulation matched the shape and timings of the first two peaks.
  - Initial thought: 1st and 2nd peak contain true profile data. Later peaks are noise from the downstream neutron target.
- However, test measurement where one pulse deliberately missed the target **still showed the same 5 peaks.**
  - All 5 peaks must be related to the beam.



Typical time structure from the benchmark IPM containing 5 peaks, seen when a fast amplifier is used for measurement



Simulated time structure of a single bunch. In this result the residual gas was modelled as 100% hydrogen.