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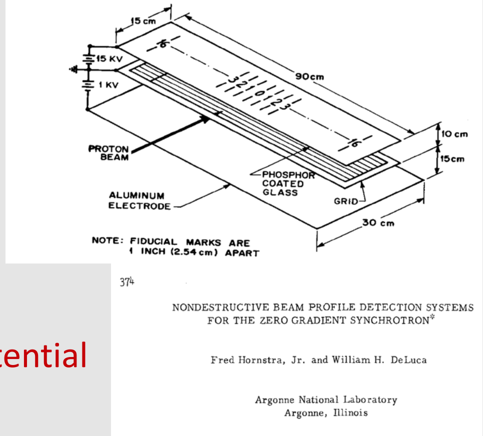
Mariusz Sapinski :: Beam Instrumentation :: Paul Scherrer Institute

Application of machine learning algorithms to the reconstruction of the actual beam profiles from the space charge distorted profiles in ionization profile monitors

5th ICFA Mini-Workshop on Space Charge, Oak Ridge, October 25th, 2022

Beam profile measurement techniques

- For hadron beams (no synchrotron radiation)
- Direct and noninvasive measurements (no Shottky, etc)
- **Light profile monitors:** register image produced by rest gas luminescence
  - very low signal, often need to inject gas, profile smeared by long-living excited states
- **Rest Gas Detectors or Ionization Profile Monitors (IPM):** extract electrons or ions produced by beam gas ionization
  - much larger signal than Light profile monitor
  - electrons move fast (single ns), their movement is affected by bunch potential
  - ions move slowly (hundreds of ns), their movement is affected by potential of multiple bunches
- **Thin target detectors:** register secondary electron emission or higher-energy secondary particles from nuclear interactions – SEM grids, wire scanners, etc.
- Other and exotic: laser wire scanner, beam gas vertex



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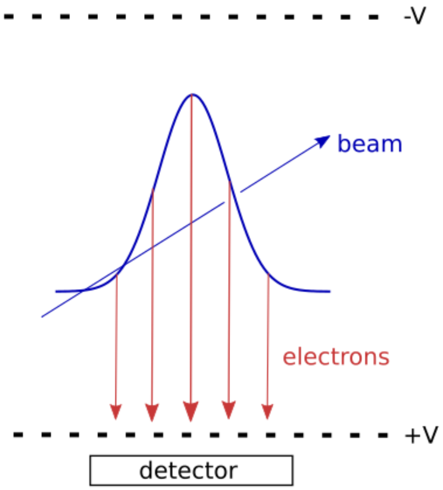
Profile distortion in IPM

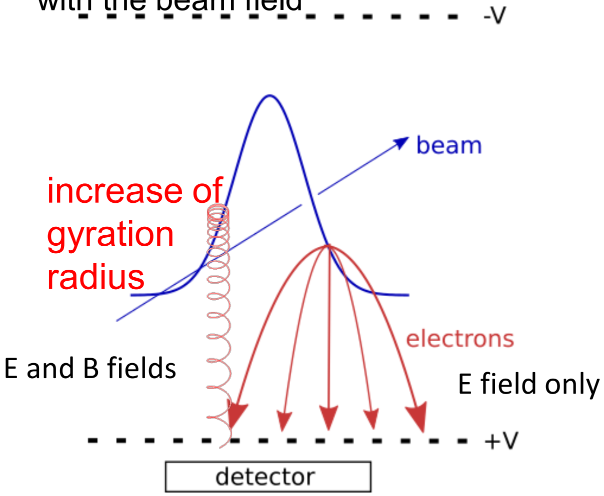
Ideal case

- 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, come on top!

Measuring ions

For ions, without magnetic field, several correction algorithms were proposed

- Effect already investigated in [W. DeLuca, IEEE 1969]
- R.E.Thern, „Space-Charge Distortion in the Brookhaven Ionization Profile Monitor ", PAC 1987

$$\sigma_m = \sigma + 0.302 \frac{N^{1.065}}{\sigma^{2.065}} (1 + 3.6 R^{1.54})^{-0.435}$$

N = beam current in 10^{12} protons

σ = root-mean-square beam size in mm.

R = aspect ratio, (other plane)/(measured plane)

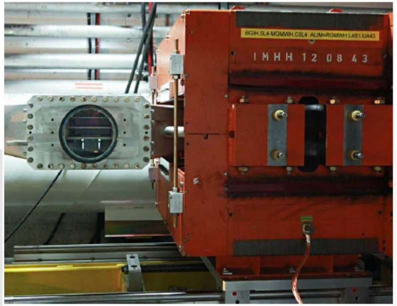
- W. Graves, "Measurement of Transverse Emittance in the Fermilab Booster", PhD 1994
- J. Amundson et al., "Calibration of the Fermilab Booster ionization profile monitor", PRSTAB 2003 (empirical)

$$\sigma_{\text{measured}} = \sigma_{\text{real}} + C_1 N \sigma_{\text{real}}^{p_1} + C_2 N^2 \sigma_{\text{real}}^{p_2}.$$

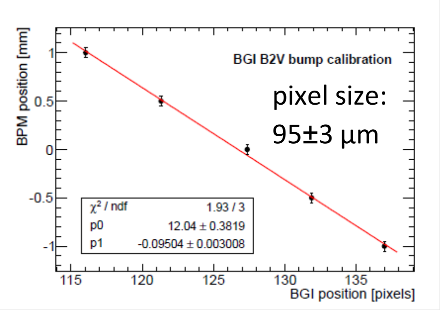
- J. Egberts, "IFMIF-LIPAc Beam Diagnostics: Profiling and Loss Monitoring Systems", PhD 2012 – nongaussian beams, solution by iterative algorithm
- Vladimir Shiltsev, „Space-charge effects in ionization beam profile monitors", Nuclear Inst. and Methods in Physics Research, A 986 (2021) 164744 - good overview and complete analytical approach
- For short and rare bunches:

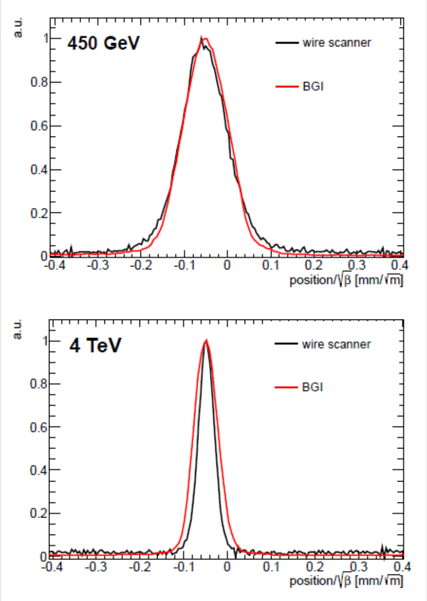
$$\sigma_m^2 = \sigma_0^2 + \kappa N_p + \kappa^2 \frac{N_p^2}{\sigma_0^2} \frac{4}{3} \ln(4/3) .$$

Measuring electrons – LHC IPM



- LHC IPM was designed to measure electrons using 0.2 T magnetic field
- Expected development: bunch-by-bunch measurement
- Electron signal amplified by MPC and registered by amplified rad hard camera
- Calibration down to 3%, but still impossible to cross-calibrate with wire scanner at high energy
- M. Sapinski et al., *The First Experience with LHC Beam Gas Ionization Monitor*, proc. of IBIC 2012 (TUPB61)
- Suspected optical PSF, MCP saturation or impact of beam space charge
- Simulation of beam space charge on low energy electrons is not trivial
- Existing codes (CST, Geant4, COMSOL) are/were missing features





Simulation of electrons moving in IPM

- Tracking code with description of ionization cross section and transient bunch field simulations is needed
- Numerous „private" codes (workshops on IPM simulations: CERN 2016, GSI 2017, J-PARC 2018)
- M. Sapinski et al.., *Ionization Profile Monitor Simulations - Status and Future Plans*, Proc. of IBIC 2016 (TUPG71)

Name/Lab	Language	Ionization	Guiding field	Beam shape	Beam field	Tracking
GSI code	C++	simple DDCS	uniform E,B	parabolic 3D	3D analytic relativ.	numeric R-K 4^{th} order
PyECLOUD-BGI /CERN	python	realistic DDCS	uniform E,B	Gauss 3D	2D analytic relativ. only	analytic
FNAL	MATLAB	simple SDCS	3D map E,B	arbitrary	3D numeric relativ. (E and B)	num. MATLAB rel. eq. of motion
ISIS	C++	at rest	CST map E only	arbitrary (CST)	2D numeric (CST) non-relativ.	numeric Euler 2^{nd} order
IFMIF	C++	at rest	Lorenz-3E map E only	General. Gauss	numeric (Lorenz-3E) non-relativ.	
ESS	MATLAB	at rest	uniform E,B	Gauss 3D	3D numeric (MATLAB) relativ.	numeric MATLAB R-K
IPMSim3D /J-PARC	python	realistic DDCS	2D/3Dmap E, B	Gauss 3D	2D numeric (SOR) relativ. only	numeric R-K 4^{th} order

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Virtual-IPM code

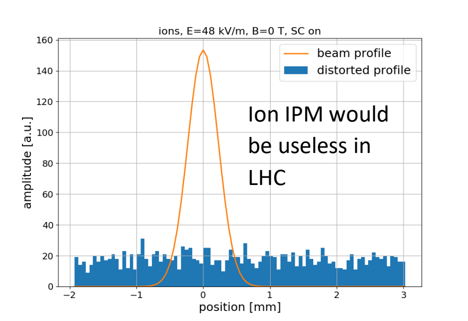
V-IPM

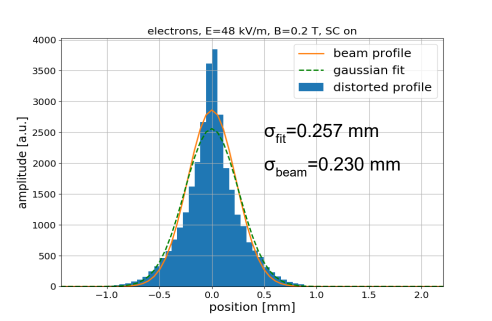
- We created new simulation code which contains all the necessary features, written in python, with modular architecture
- User Interface and Graphics in PyQt
- D. Vilsmeier, P. Forck, M. Sapinski, *A Modular Application for IPM Simulations*, Proc. of IBIC 2017 (WEPCC07)
- Publicly available and used by CERN, JPARC, GSI
- Covers: IPM, BIF, gas jets
- Benchmarked on SIS18 IPM
- Example LHC beam parameters: (and 25 ns bunch spacing) →
- Ion IPM versus electron IPM with magnetic field

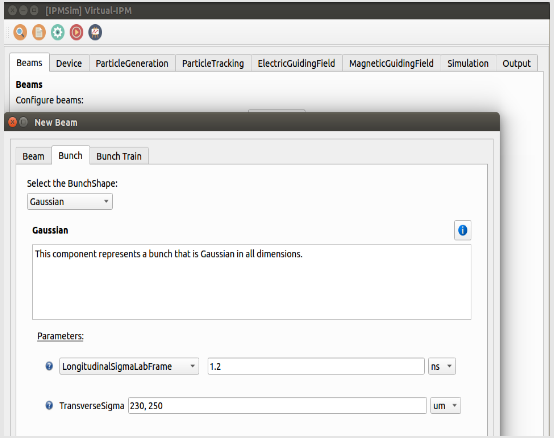
σ_x	230 μm
σ_y	270 μm
N_{prot}	$1.4 \cdot 10^{11}$
$4\sigma_z$	1.1 ns
E_{beam}	6.5 TeV

https://gitlab.com/IPMsim/Virtual-IPM

python Package Index https://pypi.org/project/virtual-ipm



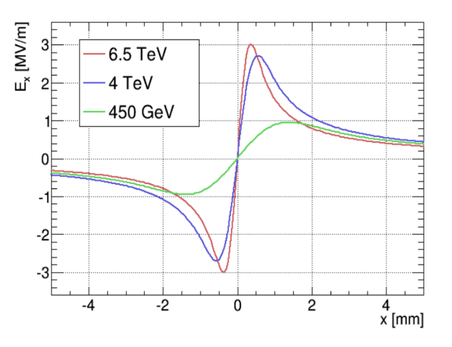


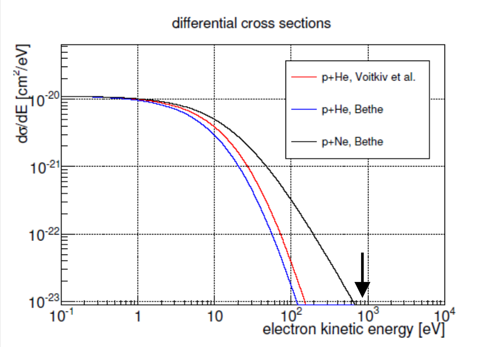


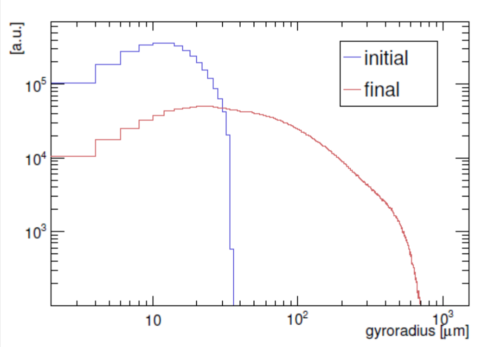
modules: eg. 2D/3D Poisson solver, analytic solution for Gaussian, etc…

What is happening with electrons?

- Bunch electric field reaches 3 MV/m (IPM extraction field 48 kV/m)
- Initial electron energy (from ionization) is very small
- Bunch field gives it a strong kick
- Increase of gyroradius by factor 10 to 100
- Even a small shift of the gyration center
- Sophisticated „electron sieve" method which filters electrons of various gyroradii can be used to reconstruct the original profile: D. Vilsmeier et al., *Investigation of the effect of beam space-charge on electrons in ionization profile monitors*, Proc. of HB2014 (MOPAB42)

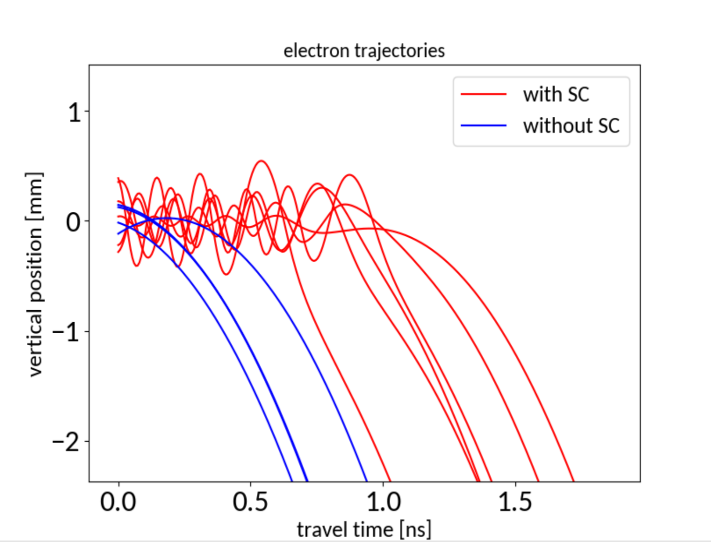


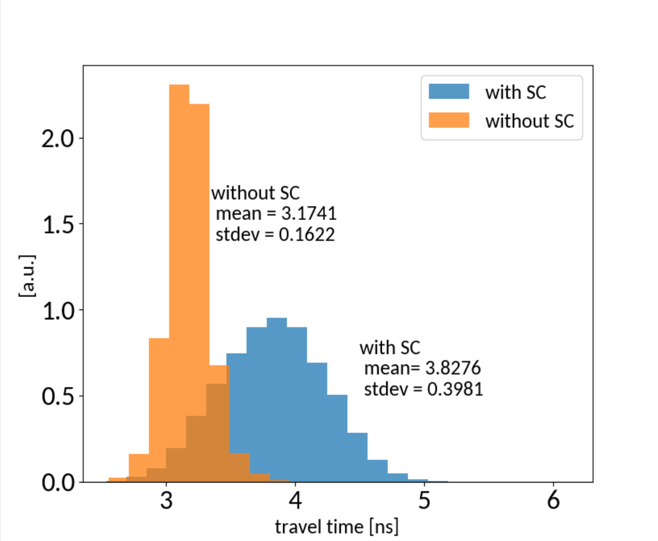




Electron trapping in the bunch

- Analysis of electron trajectories reveal trapping



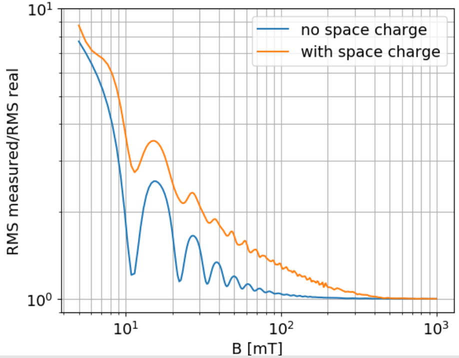


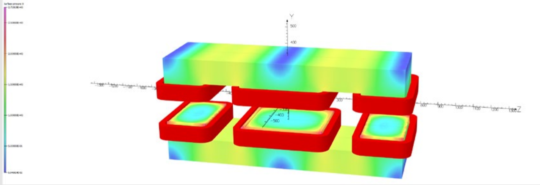
- Electrons are trapped in bunch field for the time when bunch passes.
- They make several oscillations around bunch center. Complex movement.

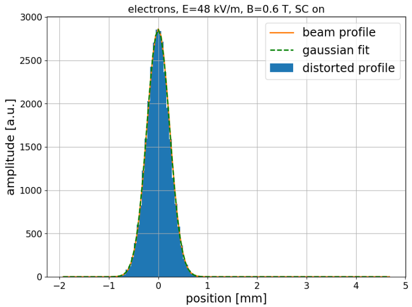
How to correct distorted profile?

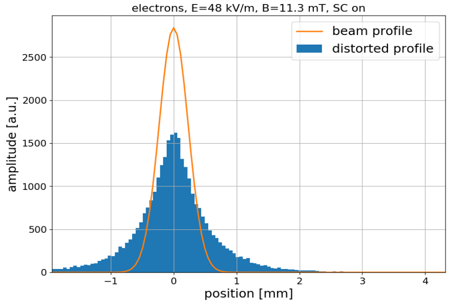
Profile distortion is nonlinear and no analytical correction formula found.
What can be done:

- Electron sieve – technically difficult and complex analysis (indirect measurement)
- Tuning the field to „single turn between beam and detector" – old good idea, but it does not work because of too big spread of electron velocities
- Increase magnetic field - CERN is considering it









- Design of 0.6 T LHC IPM magnet (D. Bodart)
- Also CERN has a very nice IPM with digital readout (Timepix3 chip)
- Go with the flow and try Machine Learning

Profile correction using Machine Learning

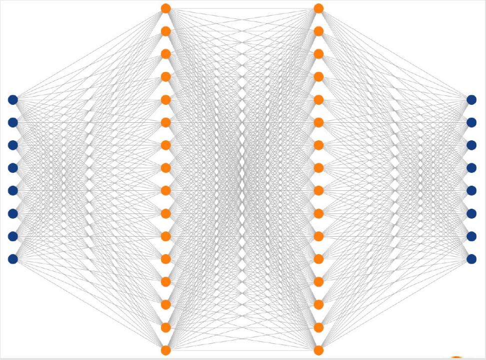
Fully-connected feed-forward network implemented in tensorflow

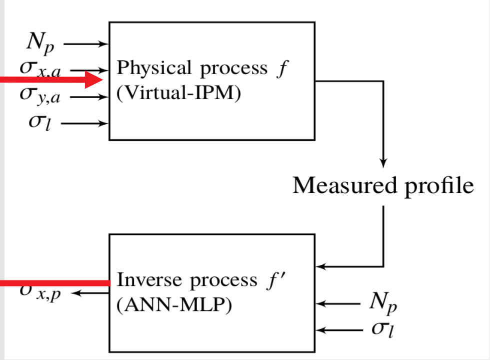
Trained and tested on simulated data

Bunch charge and length as independent input

Several approaches tried:

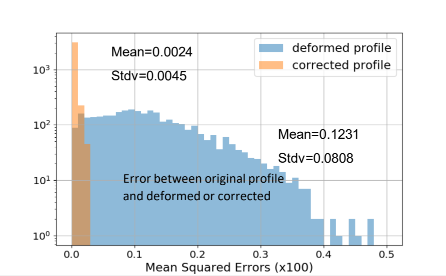
- Measured profile→original beam sigma
  - Linear regression, Kernel Ridge Regression, Support Vector Machine
  - R. Singh et al., *Simulation Supported Profile Reconstruction with Machine Learning*, Proc. of IBIC17 (WEPCC06)
- Measured profile→ original profile
  - 2-layer percepton and other architectures, fixed 98 bins
  - Trained on gaussian-only profiles
  - D. Vilsmeier et al., *Reconstructing Space-Charge Distorted IPM Profiles with Machine Learning Algorithms*, Proc. of IPAC 2018 (WEPAK008)
  - M. Sapinski et al., *Application of Machine Learning for the IPM-Based Beam Profile Reconstrunction*, Proc. of HB 2018 (THA2WE02)



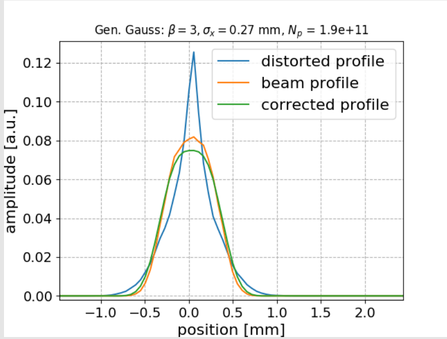


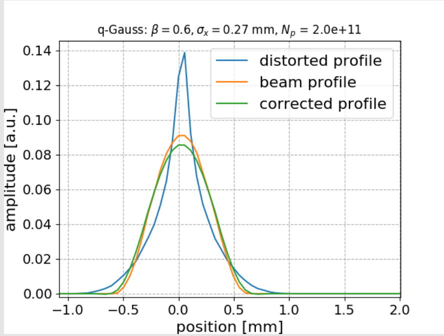
Some examples

- Network trained only on gaussian profiles
- Gaussian profiles very well corrected
- Generalized gaussians $\frac{\beta}{2\alpha\Gamma(1/\beta)} e^{-(|x-\mu|/\alpha)^{\beta}}$ also well corrected
- Q-Gaussian $\frac{\sqrt{\beta}}{C_q} e_q(-\beta x^2)$ also well reconstructed
- Can we conclude that ML model learned physics behind profile deformation?
- Summary paper: *Space-charge Distortion of Transverse Profiles Measured by Electron-based Ionization Profile Monitors and correction methods,* Phys.Rev.Accel.Beams 22 (2019) 052801
- Interesting application to XFEL – thanks to space charge possible to measure beam profiles smaller than detector resolution



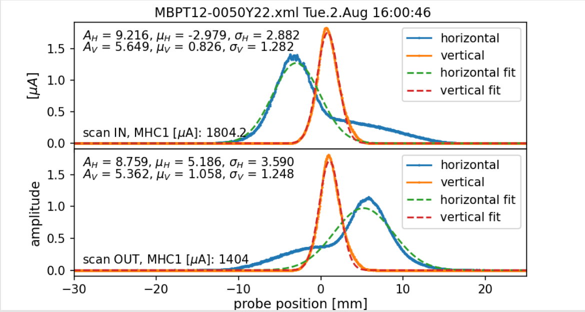
extreme cases:

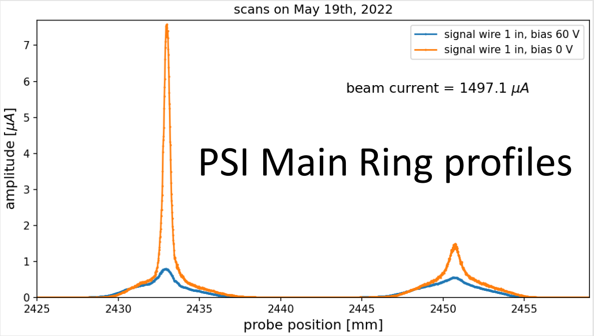


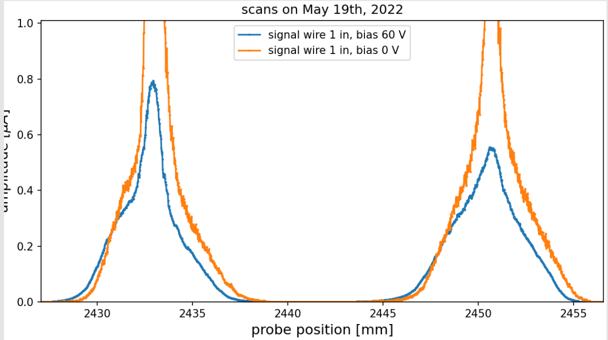


Similar problems in instrumentation

- Measurement of beam profile with wire scanner: secondary and thermionic emission
- At high beam currents thermionic emission dominates
- Thermionic emission electrons have lower energy, so applying bias voltage brings down thermionic emission contribution
- However SE electrons are also affected
- Registered profiles are deformed
- Code pyTT: adding new features eg. SEE spectrum







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Wir schaffen Wissen – heute für morgen

Summary:

- Bunch space charge affects methods to measure beam profile
- Distorsions are nonlinear
- Use of accurate simulations is crucial
- Machine Learning methods are very promising in correcting for space charge effects in instrumentation
- Problems maybe in error estimation

My thanks go to

- Dominik Vilsmeier (Frankfurt Univ.)
- Rahul Singh
- Peter Forck
- Rudolf Doelling

and thank you
for your attention!

Summary slide, 5th ICFA mini-workshop on Space Charge
Theme: Bridging the gap in space charge dynamics

In 1-2 sentences, summarize the content of this presentation
(If relevant, specify type of facility, species, tune shift):

Space charge maybe also a problem for beam measurement techniques. Devices like beam fluorescence monitors, ionization profile monitors or even SEM grids and wire scanners can produce inaccurate results.

From your perspective, where is the gap regarding space charge effects?
(understanding/control/mitigation/prediction/?)

There was (still is?) lack of coherent effort between labs to develop theory and simulation tools.

What is needed to bridge this gap?

Instrumentalists are trying to collaborate, this audience should be aware of challenges and support efforts.