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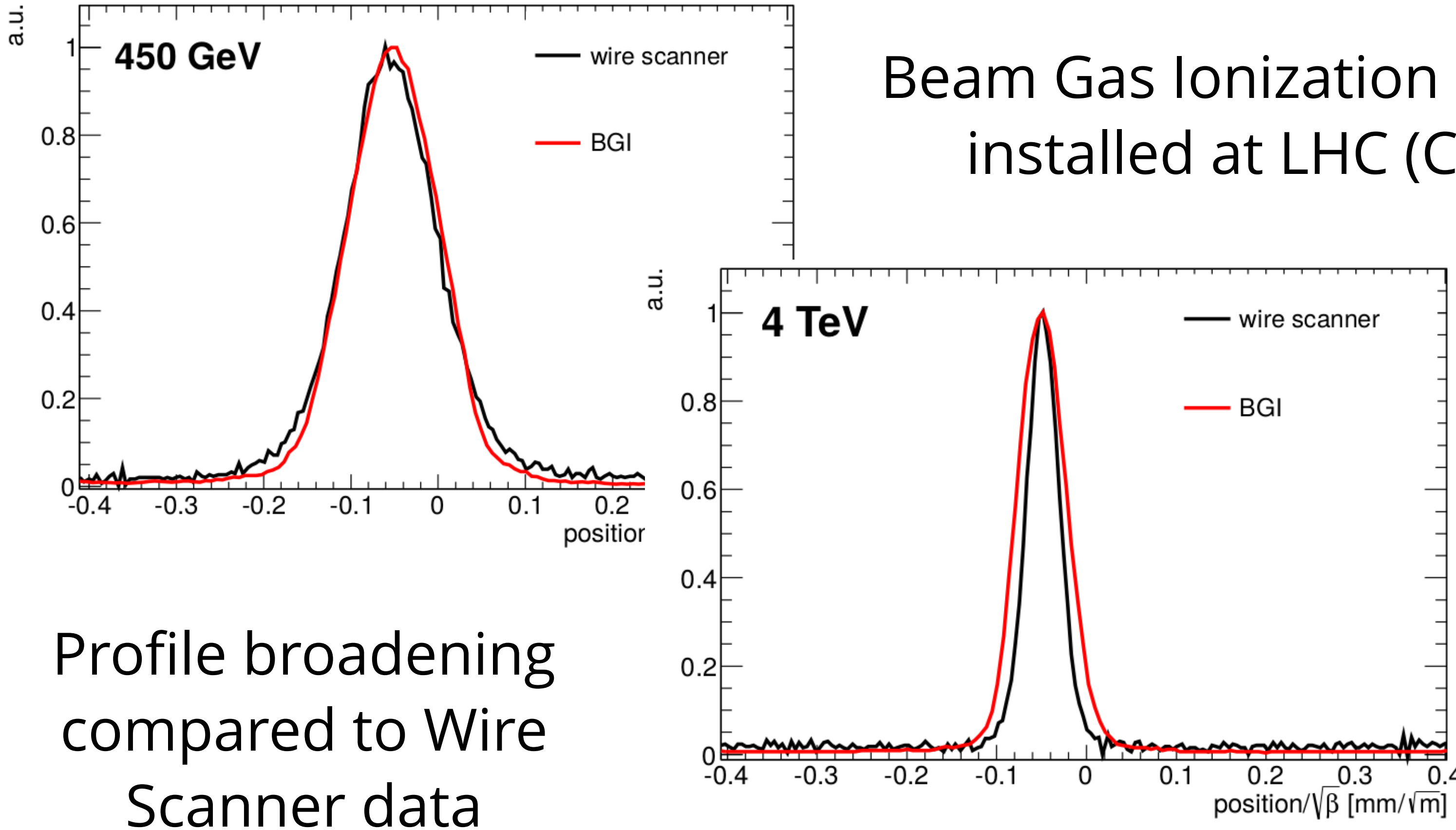
Comprehensive simulations of distortions and their mitigations related to measurements with ionisation profile monitors

Dominik Vilsmeier / GSI

1st ARIES Annual Meeting
Riga Tech. Univ., Latvia
May 24th, 2018

Preface

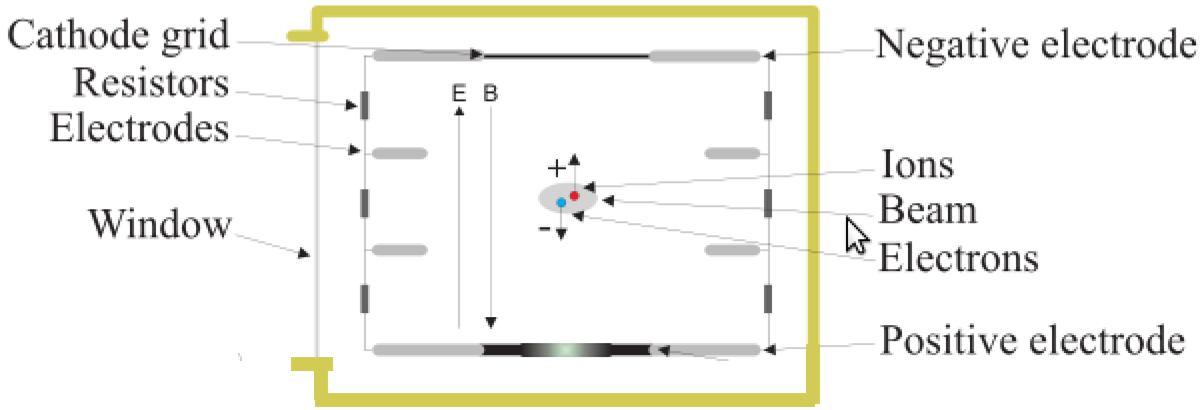


Beam Gas Ionization Monitor installed at LHC (CERN)

Profile broadening compared to Wire Scanner data

M. Sapinski et al 2012 "The first experience with LHC Beam Gas Ionization Monitor" *Proc. IBIC2012*

Profile broadening - why?



- ✗ Effects related to MCP
- ✗ Optical point-spread function
- ✓ Distortion of electron trajectories due to beam space charge
- ✓ Distortion due to electron gyroradius

Simulations

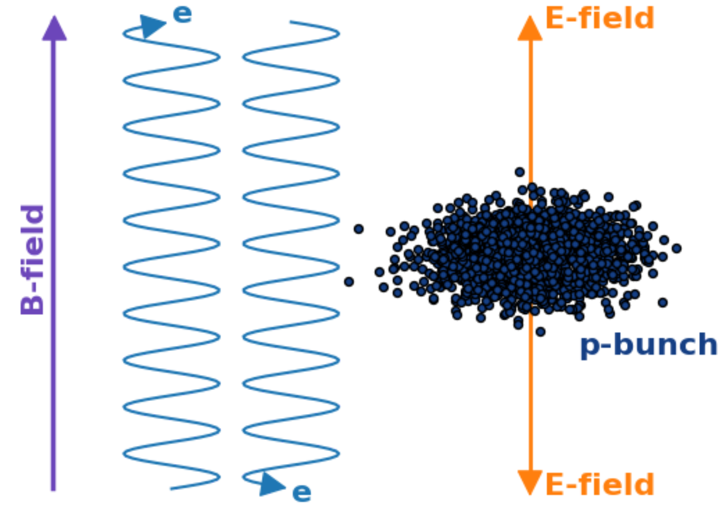
Available

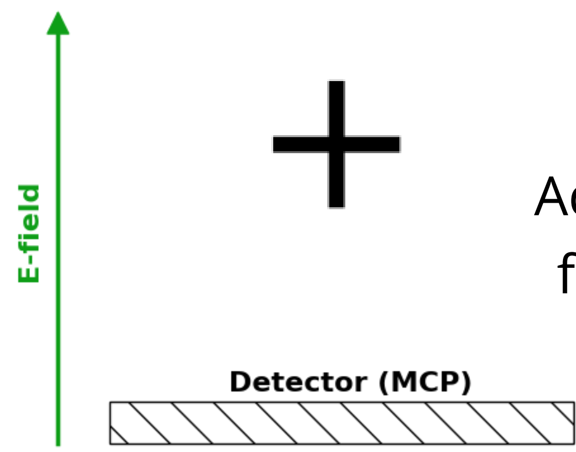
PyECLOUD
(electron cloud
studies)

↓

Upgrade

PyECLOUD-BGI
(electron
movement in IPM)





Adaption
for IPM

Workshop @ CERN | 2016

Workshop @ CERN | 2016

- Design of electrodes for new devices
- Simulation of field configuration for removing electron cloud from the device volume
- Simulation of profile distortion

- Simulation code involving ionization and transport of electrons in realistic fields
- Code base with core developers
- Infrastructure for code maintenance and user support

Simulation codes

Name	Year	Implementation	Fields	Beams	Remarks	Contact	Public
ESS code	2016	Matlab	E, B	Relativistic	Currently being benchmarked	Jacques Marroncle	✗
IPMSim3D	2015	Python	E, B	Relativistic		Kenichiro Satou	✓
ISIS code	2014	C++	E	Non-relativistic ions (DC beams)		Rob Williamson	✗
PyECLOUD-BGI	2013	Python	E, B (uniform)	Relativistic Gaussian	Stable version	Dominik Vilsmeier	✓
IFMIF code	2013	C++	E	Non-relativistic ions	Development abandoned	Jacques Marroncle	✗
GSI code	2010	C++	E, B	Non-relativistic and relativistic Ellipsoidal	Currently in revision	Peter Forck	✗
FNAL code		Matlab	E, B	Any		Randy Thurman-Keup	✗

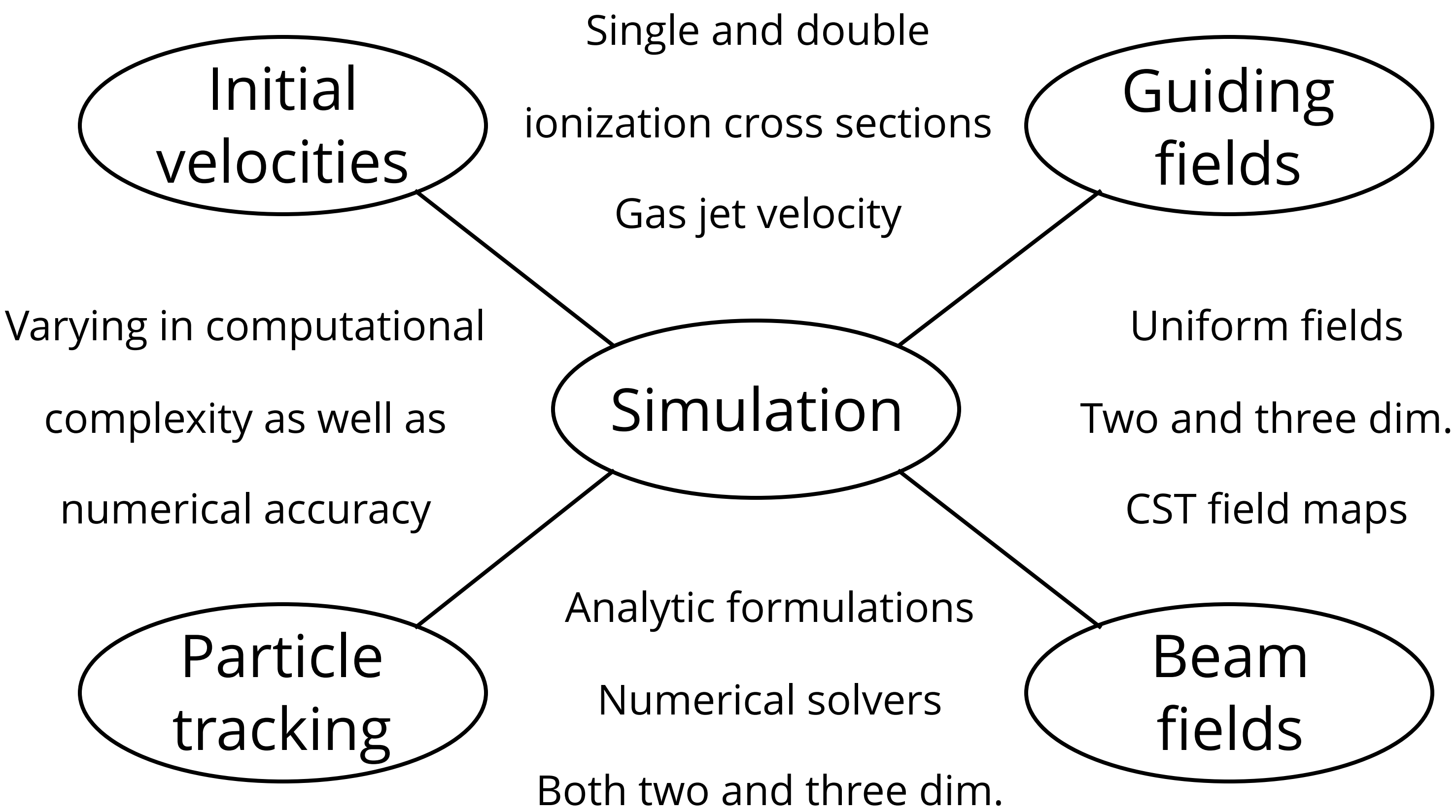
Various programs / scripts:

- different applications (LINAC, Synchrotron, ...)
- different solutions

Combine the effort and create a common tool

→ suitable for all different use cases

Code modularity



Workshop @ GSI | 2017

Sponsored by ARIES

33 participants

13 institutes

9 countries

BROOKHAVEN NATIONAL LABORATORY

Science & Technology Facilities Council
ISIS Neutron and Muon Source

The Cockcroft Institute of Accelerator Science and Technology

OAK RIDGE National Laboratory

Fermilab

MedAustron

J-PARC

BINP

GSI

JÜLICH Forschungszentrum

cea

CERN

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Compilation of IPM realization

Operational issues

Simulation code innovation

Present the new simulation tool

Collect feedback from the community

Benchmark simulation against each other

Perform measurements for comparison with data

Discuss new use cases and applications

Investigate corresponding models

Virtual-IPM

- Emphasis on flexibility and extensibility
- Covers a broad range of use cases
- Acts as framework as well as stand-alone application
- Suitable for developers and users

```
$ pip install virtual-ipm  # Easy installation
```

https://pypi.org/project/virtual-ipm

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

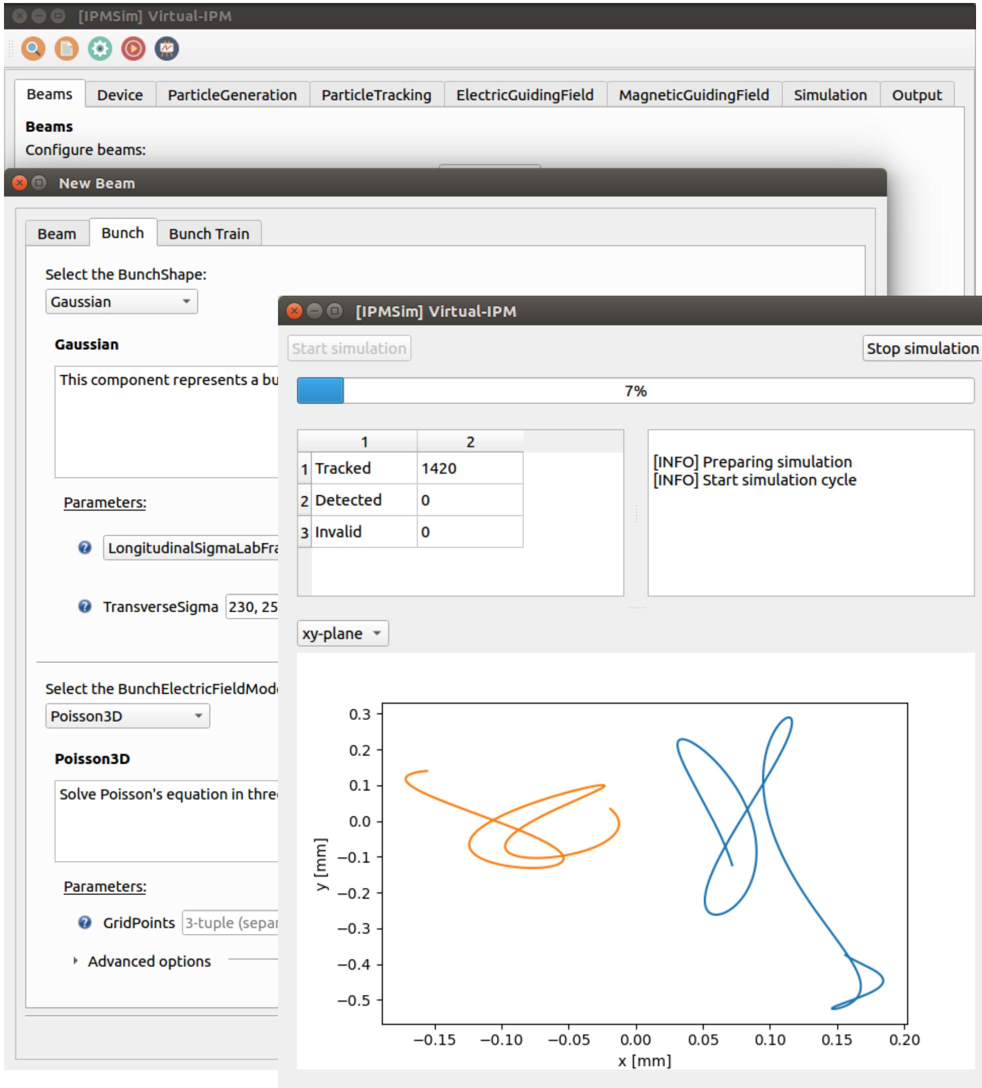
Graphical User Interface

```xml
<?xml version="1.0" ?>
<Virtual-IPM version="1.2.2">
  <Beams>
    <Beam>
      <Parameters>
        <Energy unit="TeV">6.5</Energy>
        <BunchPopulation>2.1e+11</BunchPopulation>
        <ParticleType>
          <ChargeNumber>1</ChargeNumber>
          <RestEnergy unit="MeV">
            %(proton mass energy equivalent in MeV)
          </RestEnergy>
        </ParticleType>
      </Parameters>
```

```
dominik@MyPC: ~
(virtual-ipm-dev) dominik@MyPC:~$ virtual-ipm --help
usage: virtual-ipm [-h] [--version] [--quiet-console]
                   [--console-log-level [{debug,info,warning,error,critical}]]
                   [--log-to-file LOG_TO_FILE]
                   [--file-log-level [{debug,info,warning,error,critical}]]
                   [--timing-stats-to-file TIMING_STATS_TO_FILE]
                   config

positional arguments:
  config                File path pointing to a configuration file.

optional arguments:
  -h, --help            show this help message and exit
  --version             show program's version number and exit
  --quiet-console       Use this switch to suppress all console output.
  --console-log-level [{debug,info,warning,error,critical}]
                        Set the logging level to one of the levels available
                        in the Python logging library.
  --log-to-file LOG_TO_FILE
                        In addition to the console log entries will be stored
                        in the specified file.
  --file-log-level [{debug,info,warning,error,critical}]
                        The level for file logging can be set independently
                        from the console.
  --timing-stats-to-file TIMING_STATS_TO_FILE
                        The timing (performance) statistics will be written to
                        the specified file.
```



Graphical User Interface

XML configuration format

- Descriptive and clear
- Easy in-file modifications

Command Line Interface

- Straightforward access to simulations
- Provides feedback about status

Graphical User Interface

- Adaptive - Enhancements to the code are readily reflected in the GUI

Use cases

IPM Profile distortion

- Guiding field non-uniformities
- Beam space-charge interaction
- Influence of ionization momenta

- IPM Profile "rectification", e.g. through device upgrades or software based solutions

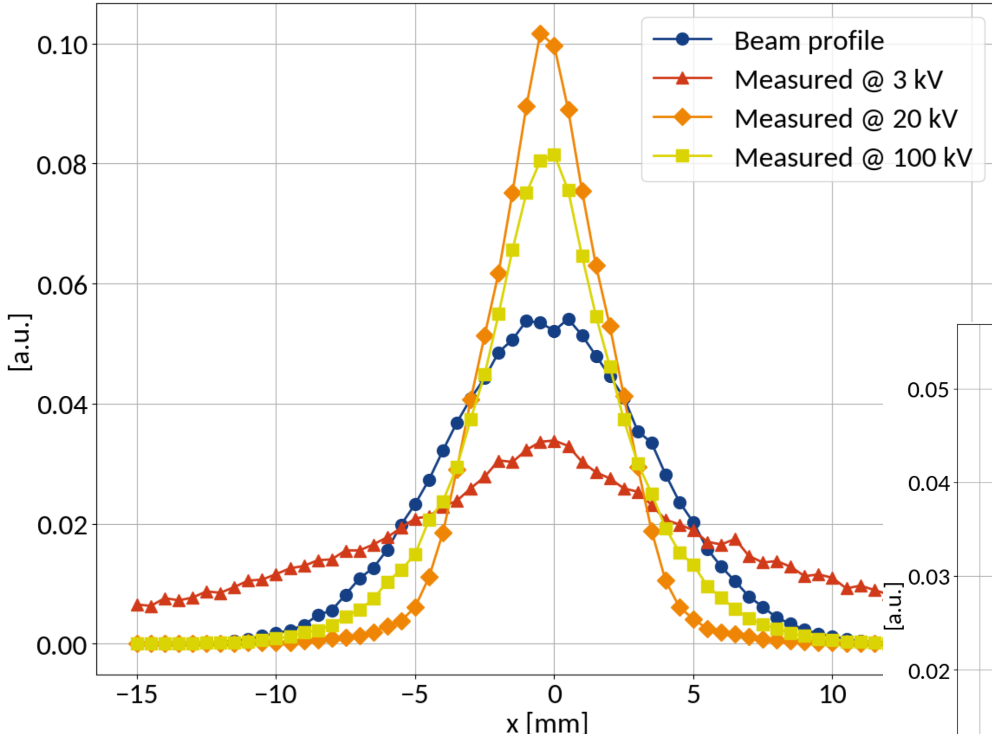
IPM Design

- Field cage design
- Magnetic field strength required for suppressing distortions

BIF space-charge effects

- Excited ions move under the influence of beam fields
- Gas jet velocity is retained by ions

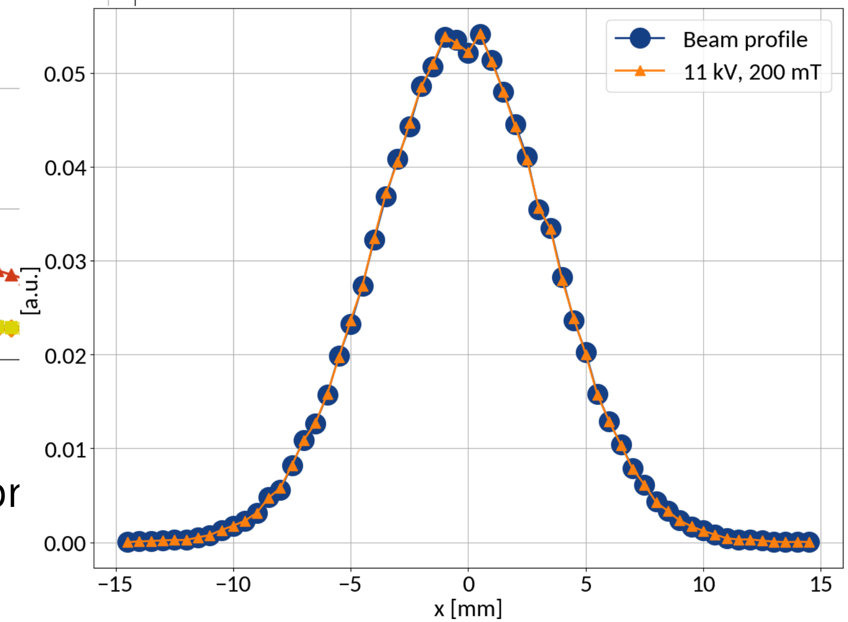
PS IPM Design



Energy	25 GeV
Bunch pop.	1.33e11
Bunch size	3.7 x 1.4 mm
- length (4σ)	3.0 ns

Profile distortion cannot be sufficiently suppr

by electric field



Confirming the requirement for a

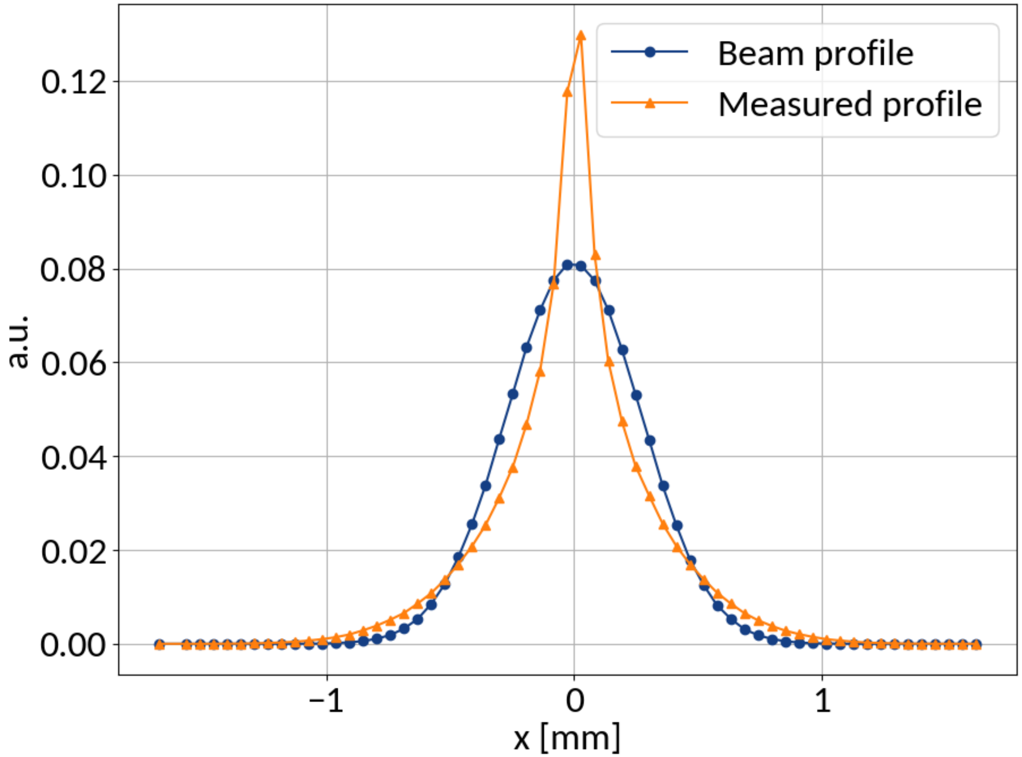
magnetic guiding field

IPM & Beam parameters

Beam Parameter	Value
Particle type	Protons
Energy	25 GeV
Bunch pop.	1.33e11
Bunch width (1σ)	3.7 mm
Bunch height (1σ)	1.4 mm
Bunch length (4σ)	3.0 ns

IPM Parameter	Value
Electrode distance	70 mm
Applied voltage	11 kV
Applied magnetic field	0.2 T

LHC Profile distortion



Beam	
Energy	6.5 TeV
Bunch pop.	2.1e11
Bunch size	270 x 360 μm
- length (4σ)	0.9 ns

IPM	
Electrode dist.	85 mm
Applied voltage	4 kV
Magnetic field	0.2 T

IPM & Beam parameters

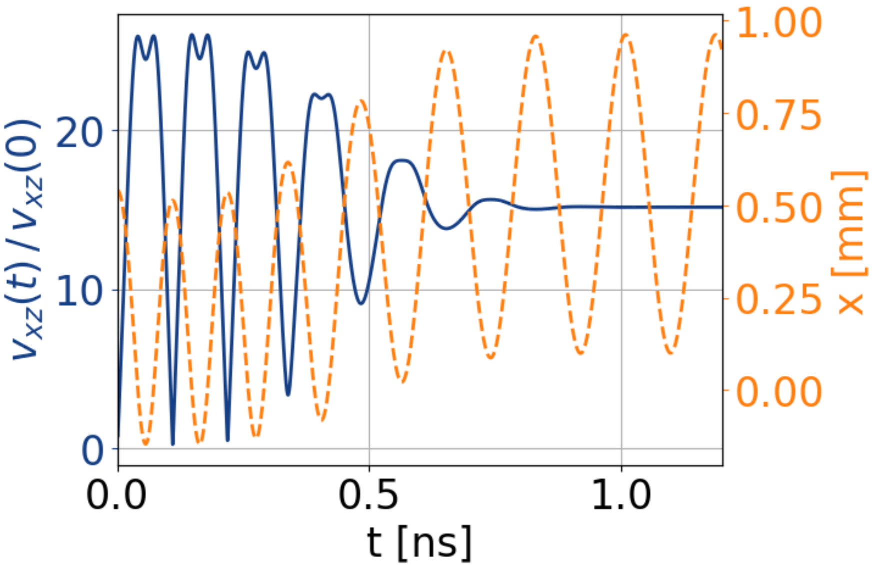
Beam Parameter	Value
Particle type	Protons
Energy	6.5 TeV
Bunch pop.	2.1e11
Bunch width (1σ)	270 μm
Bunch height (1σ)	360 μm
Bunch length (4σ)	0.9 ns

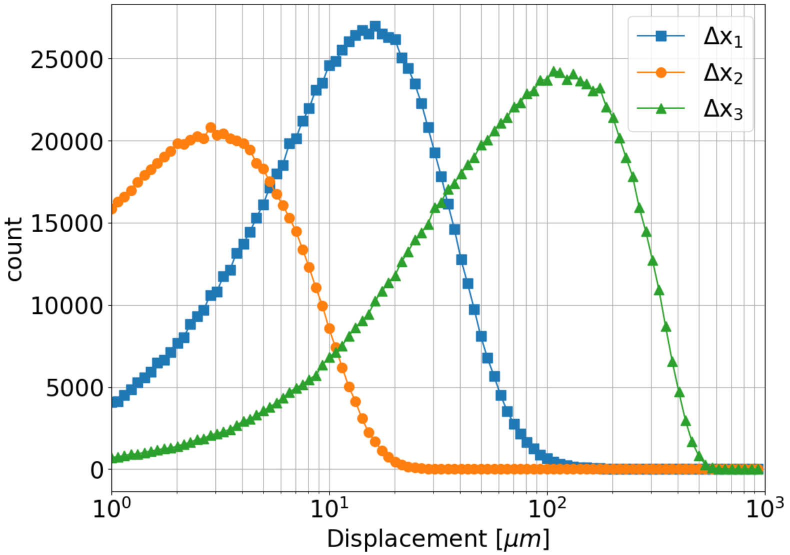
IPM Parameter	Value
Electrode distance	85 mm
Applied voltage	4 kV
Applied magnetic field	0.2 T

LHC Profile distortion

Gyro-velocity oscillates due to ExB-drift

Electrons end up with increased velocity





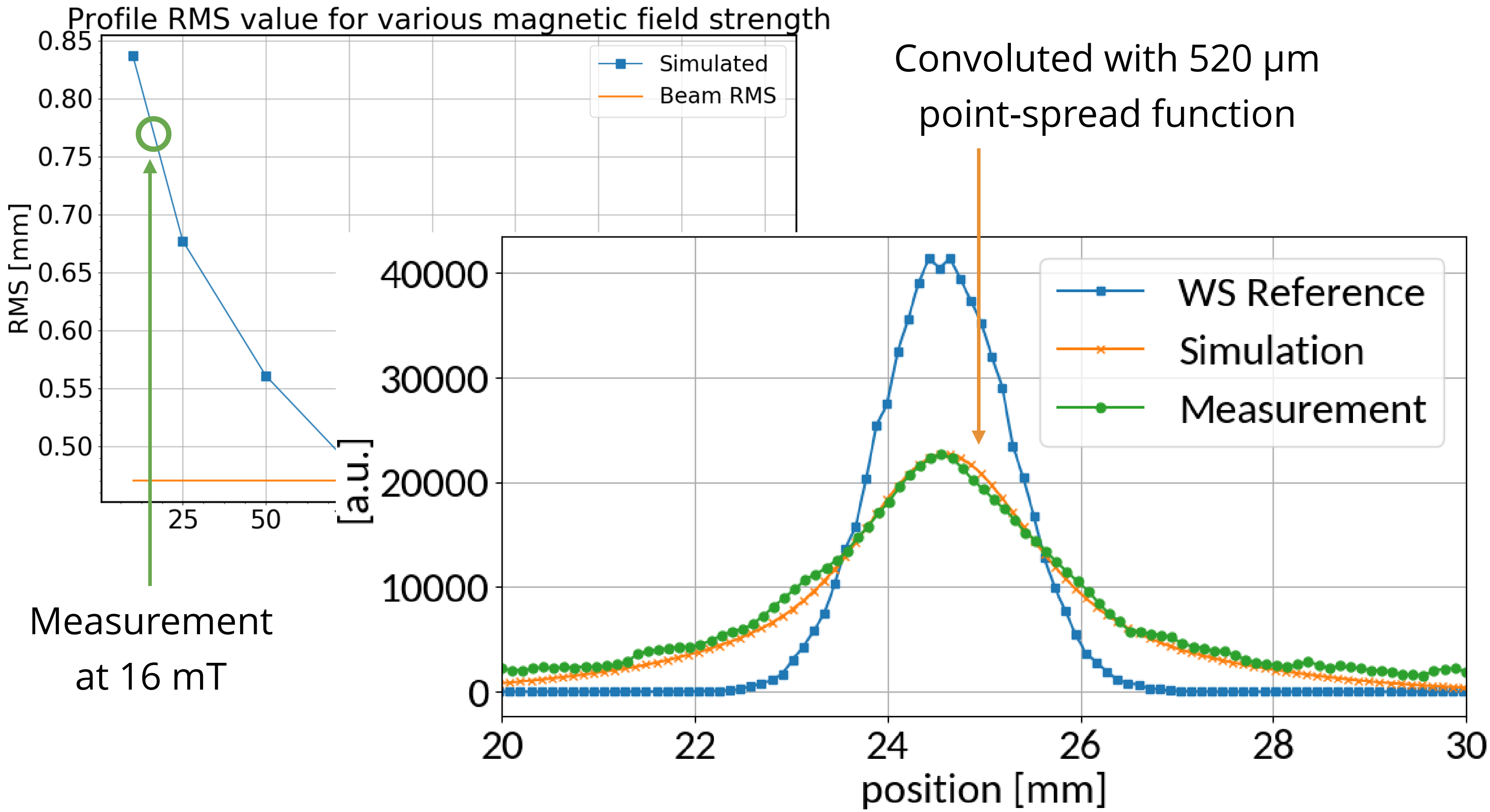
Displacement due to ...

... ionization (Δx1)

... space-charge (Δx2)

... gyro-motion (Δx3)

SPS Profile distortion

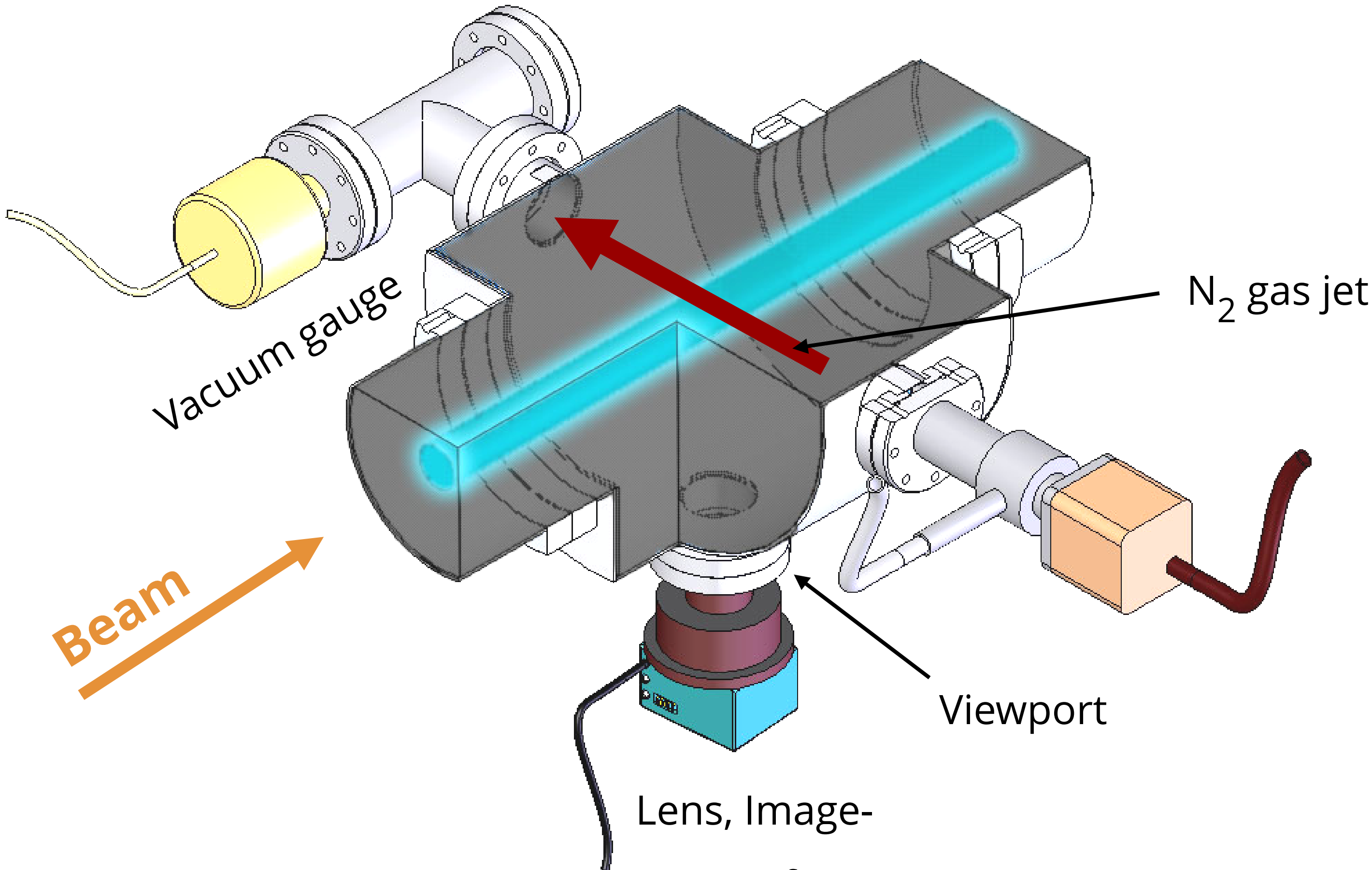


IPM & Beam parameters

Beam Parameter	Value
Particle type	Protons
Energy	450 GeV
Bunch pop.	2.86e11
Bunch width (1σ)	835 μm
Bunch height (1σ)	451 μm
Bunch length (4σ)	1.6 ns

IPM Parameter	Value
Electrode distance	70 mm
Applied voltage	4 kV
Applied magnetic field	16 mT

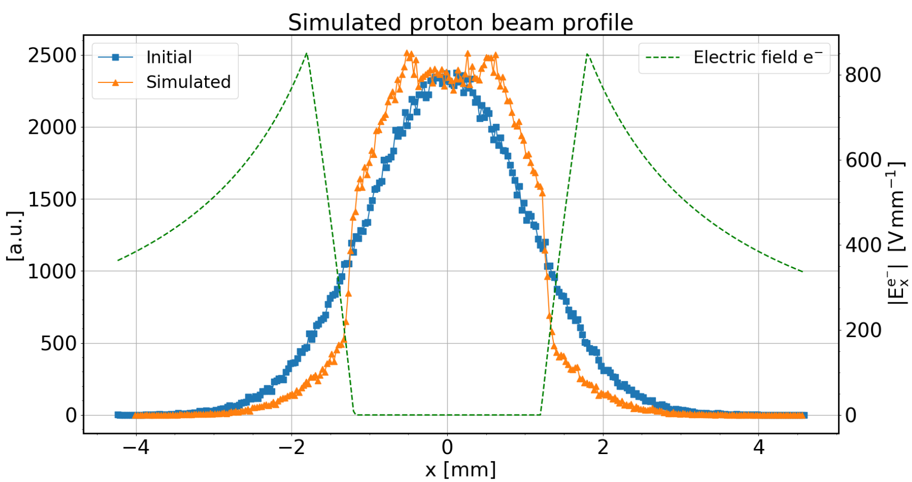
BIF for e-Lens @ HL-LHC

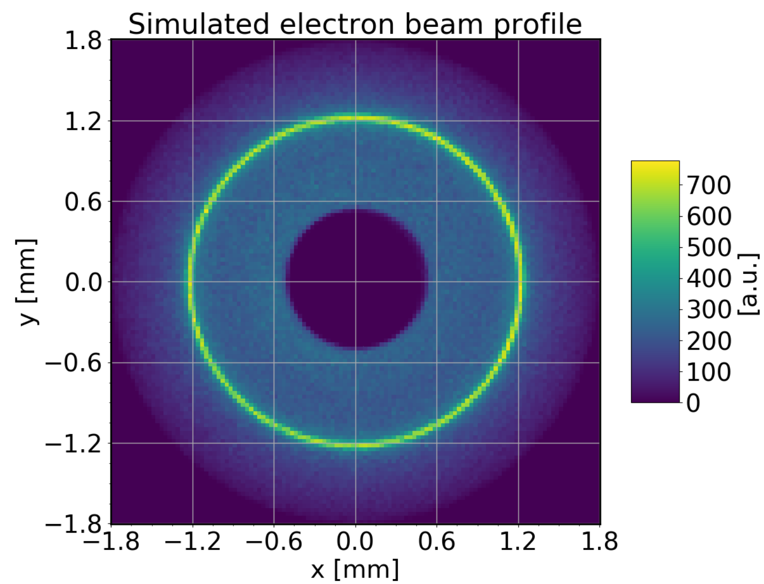


BIF schematic

BIF for e-Lens @ HL-LHC

Simulation of complex setup for diagnostics based on BIF with supersonic gas jet





Excited ions interact with beam fields and suffer from a displacement until they decay

BIF & Beam parameters

Preliminary parameters; S. Udrea et al "Preparatory work for a fluorescence based profile monitor for an electron lens" Proc. IBIC2016

p-Beam Parameter	**Value**
Particle type	Protons
Energy	7 TeV
Bunch pop.	2.2e11
Bunch width (1σ)	1.02 mm
Bunch height (1σ)	1.02 mm
Bunch length (4σ)	1.25 ns

e-Beam Parameter	**Value**
Particle type	Electrons
Type	DC beam
Energy	10 keV
Beam current	4 A
Inner radius	1.2 mm
Outer radius	1.8 mm

BIF Parameter	**Value**
Gas jet	800 m/s, 30 K
N2+* lifetime (391 nm)	60 ns

e-Lens: Additional 4 T long. magn. field

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Profile reconstruction

Machine Learning

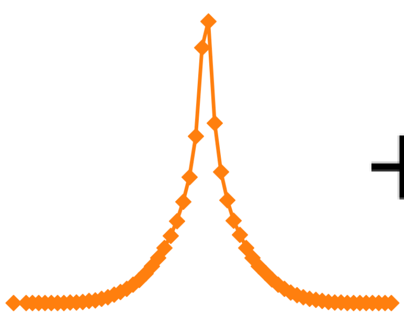
... can be used for establishing a relationship between measured profiles and beam profiles.

This relationship is inferred using data obtained from IPM simulations.

E.g. deep learning

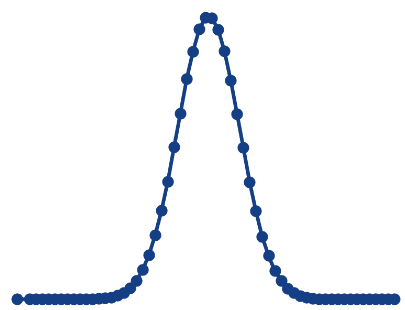
TensorFlow

Keras



Measured profile

+ Beam pars. →



Beam profile

IPM & Beam parameters

Beam Parameter	Value
Particle type	Protons
Energy	6.5 TeV
Bunch pop. [1e11]	1.1 – 2.1 ppb
Bunch width (1σ)	270 – 370 μm
Bunch height (1σ)	360 – 600 μm
Bunch length (4σ)	0.9 – 1.2 ns

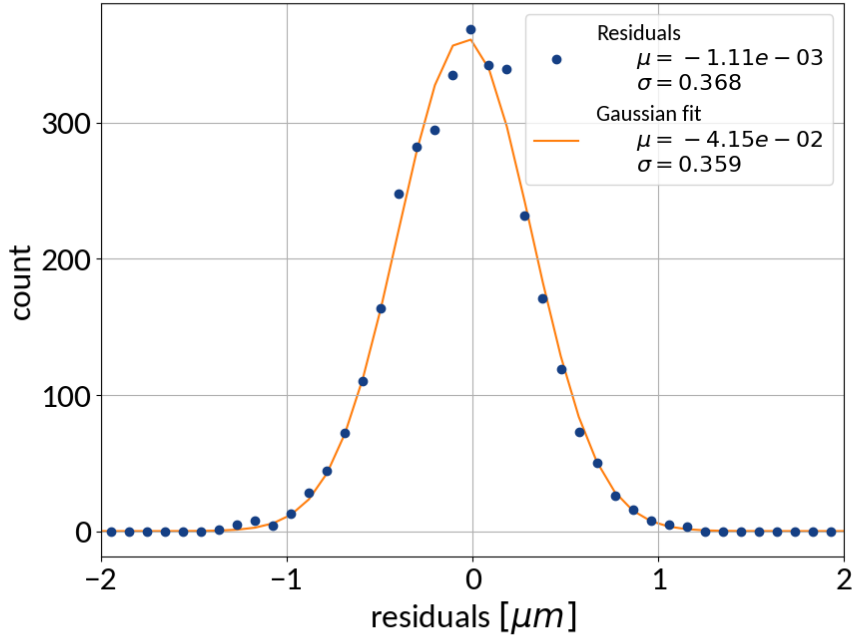
IPM Parameter	Value
Electrode distance	70 mm
Applied voltage	4 kV
Applied magnetic field	0.2 T

Profile reconstruction

Application of Machine Learning for deducing the relation between measured (distorted) and original beam profiles

Parameter	**Range**
Bunch pop. [1e11]	1.1 – 2.1 ppb
Bunch width (1σ)	270 – 370 μm
Bunch height (1σ)	360 – 600 μm
Bunch length (4σ)	0.9 – 1.2 ns

Sweep the relevant parameter space and use simulation data for training



Very good results for testing with simulation data
→ first tests with measurement data are planned

Conclusions

Lots of advancement in the field of IPM simulations

The efforts were combined into a common and generic simulation tool

Allows for simulating a broad range of cases, including LINACs, Synchrotrons and other beam instruments such as BIF monitors

Simulations are not only useful concerning IPM design but can also be used for software-based profile reconstruction (work in progress)

The community efforts have led to an established collaboration concerned about topics related to simulations of IPMs and similar beam instruments

https://ipmsim.gitlab.io/IPMSim

Thank you

Realization of the various tasks was possible thanks to the active participation of:

Peter Forck [1]

Mariusz Sapinski [1]

Kenichirou Satou [2]

Rahul Singh [1]

James Storey [3]

Serban Udrea [1]

[1] GSI [2] J-PARC/KEK [3] CERN

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