A MODULAR APPLICATION FOR IPM SIMULATIONS

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Abstract

Simulating the electron and ion tracking in Ionization Profile Monitors is an important tool for specifying and designing new monitors. It is also essential for understanding the effects related to the ionization process, guiding field non-uniformities and influence of the beam fields which may lead to a distortion of measured profiles. Existing simulation codes are often tuned to the specific needs of a laboratory, are not well documented and lack a practical user interface. This work presents a generic simulation tool which combines the features of existing codes in order to provide a common standard for IPM simulations. The modular structure of the application allows for exchanging the computational modules depending on the use case and makes it extensible to new use cases. By this means simulations of Beam Induced Fluorescence monitors based on supersonic gas jets have been realized. The application and all involved methods have been tested and benchmarked against existing results. The code is well documented and includes a graphical user interface. It is publicly available as a git repository and as a Python package.

INTRODUCTION

Ionization Profile Monitors (IPM) allow for measuring the transverse profile of particle beams. They take advantage of the ionization process which is induced by the interaction of the particle beam with the (rest) gas and measure the resulting ionization products. An electric field is used for guiding ionized electrons or ions towards an acquisition system.

Several simulation codes have been developed at different accelerator laboratories in order to study effects which influence the quality of measured profiles or to design new devices [1, 2]. Two workshops dedicated to IPM simulations [3, 4] have shown a broad interest in this topic and also revealed the benefits of combining efforts and existing developments into a single application. For that reason the idea of a common, generic simulation tool was born. This application shall include the features of existing codes as well as be extensible to new methods.

USE CASES

While the motivation for such an application emerged mainly from simulations of IPMs it can be easily extended to other beam instruments such as Beam Induced Fluorescence monitors (BIF) or Electron Wire Scanners. Because such simulations involve many similarities it is useful to include them into a single application (in order to reuse the relevant parts for the different scenarios). For IPM simulations the influence of beam space charge [5, 6] or guiding field non-uniformities [7] are interesting subjects to study. Also the effect of secondary electrons emerging from ion impact on detector elements can be important to estimate. Other scenarios include the usage of supersonic gas jets for IPMs and BIFs or simulations of Electron Wire Scanners. Simulations involving the influence of multiple beams, for instance in case of diagnostics for electron lenses, are also of great interest.

MODULES

In order to fulfill the above mentioned use cases, common aspects have been separated into different modules and were realized in form of the following models. A model is a specific implementation for a given module, applicable to one or more specific use cases. The structure of the simulation framework, including the different modules and models, is shown in Fig. 1.

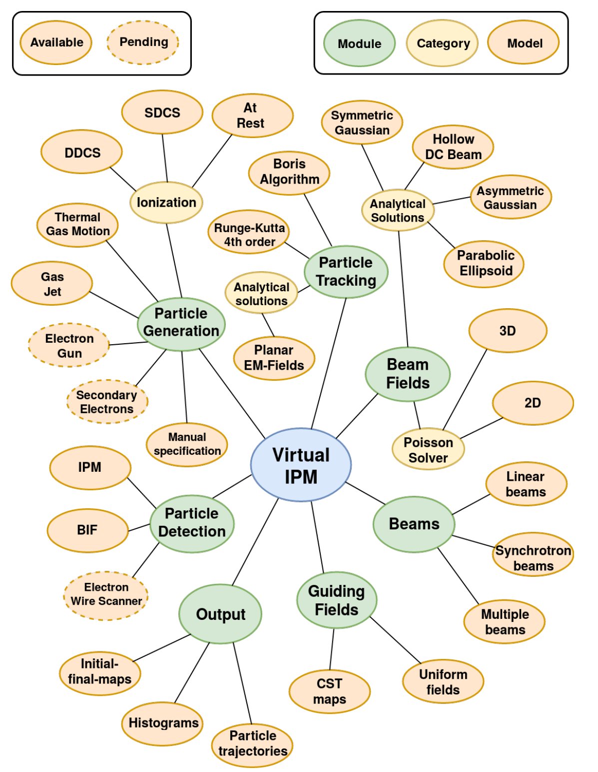

Figure 1: The different components (modules) of the simulation framework together with their corresponding models. Dashed ellipses indicate models in development.

Particle Generation

Particle generation models define the initial parameters for particles when they enter the simulation. Typically this involves the ionization or excitation process induced by the particle beam however other methods are possible (for example secondary electron generation). The following methods

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for sampling the initial momenta of ionized particles are available:

- Double differential cross sections [8]
- Thermal rest gas motion
- Gas jets
- Generate at rest, i.e. with zero momentum

Particle Tracking

Particle tracking models are responsible for updating the particles' positions and momenta at each simulation step hence they propagate the particles during the simulation. Both accuracy and efficiency are desirable for such computationally heavy methods. They commonly involve a trade-off between the number of steps and the accuracy when tracking for a given time, in form of a time step size Δt for which a single update is performed. Running a few cases with varied Δt and observing the resulting trajectories to converge is usually a good indicator for a sufficiently small time step size. The following methods are available for particle propagation:

- Runge-Kutta method of 4th order
- Boris algorithm [9]
- An algorithm which is based on the analytical solution of the equations of motion for uniform planar electromagnetic fields [10]

Particle Detection

Particle detection models define when the tracking for a particle should stop because it was either detected or it reached an invalid state (e.g. because it hit a boundary of the chamber).

The current implementations include an IPM model which supports tracking until particles reach a specific position (the detector) and a BIF model which determines the decay of excited states based on a pseudo-random statistical process corresponding to spontaneous emission (a particle is considered *detected* when its excited state decays).

Guiding Fields

Guiding field models describe the external electric and magnetic fields which are used to guide and to confine the tracked particles. Different models for emulating uniform fields or for loading CST field maps are available.

Beam Fields

One main purpose of running such simulations is to study the influence of the electromagnetic fields of particle beams on the movement of ions and electrons. The electric field of a bunch is computed in the rest frame of that bunch and then transformed to the laboratory frame in order to obtain the electromagnetic field as seen by the non-relativistic ionization products. Various models for the electric field computation are available ranging from analytical solutions for specific charge distributions to numerical Poisson solvers which can handle arbitrary charge distributions. The available implementations include:

- Analytical solutions for two-dimensional Gaussian charge distributions (the longitudinal field component is neglected) [11]
- Analytical solution for a parabolical-ellipsoidal charge distribution [12]
- Analytical solution for a hollow DC beam
- Numerical Poisson solvers for two- and three-dimensional (arbitrary) charge distributions

COMPARISON WITH EXISTING CODES

Two benchmark cases have been established for the comparison amongst simulation codes. Table 1 contains the parameters for those two cases (LHC & PS case) which have been explored already by the following two well-established IPM simulation codes:

- **PyECLOUD-BGI** [13]: This code uses an analytical solution for the electric field of a two-dimensional elliptical Gaussian charge distribution. The beam magnetic field is neglected. The guiding fields are assumed to be uniform. The tracking algorithm is based on the analytical solution for a uniform planar electromagnetic field configuration. The initial electron momenta are sampled from a double differential ionization cross section.
- **JPARC-Code** [14]: This code uses a two-dimensional Poisson solver in order to compute the transverse electric field of the bunch's charge distribution. The beam magnetic field is neglected. Fields maps as generated by for example CST Studio or uniform fields are used for the guiding fields. The tracking algorithm uses the Runge-Kutta method of 4th order. The initial electron momenta are sampled from various ionization cross sections.

Table 1: Parameters for the Studied Benchmark Cases and the SIS-18 Measurements ("B." abbreviates "Bunch")

Case	LHC	PS	SIS-18
Particle type	Protons	Protons	$^{124}Xe^{43+}$
Energy/u [GeV]	6500	25	0.6
B. pop. [1×10^{11}]	1.3	1.33	0.02
B. length ($4\sigma_z$) [ns]	1.25	3.0	44
B. width ($1\sigma_x$) [mm]	0.229	3.7	7.81
B. height ($1\sigma_y$) [mm]	0.257	1.4	2.03
Electrode dist. [mm]	85	70	180
Applied voltage [kV]	4	20	0.8
Magnetic field [T]	0.2	$0^{\dagger}$	0

† The actual PS IPM uses a magnet generating 0.2 T field strength.

Figures 2 and 3 show the results of the comparison which are in good agreement. The computational methods which are used by the respective reference code were selected for the comparison.

Unfortunately, to our best knowledge, no good experimental IPM data for those two cases were available by the moment of this publication.

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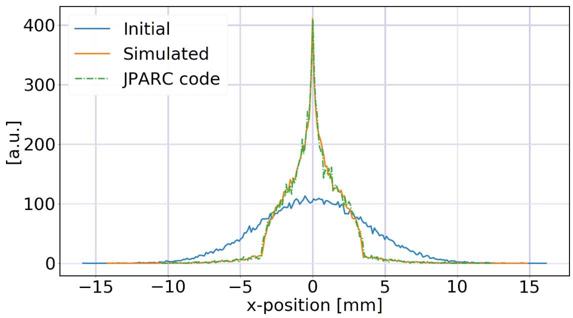

Figure 2: Comparison of simulated profiles with the JPARC code for the PS case (electron tracking).

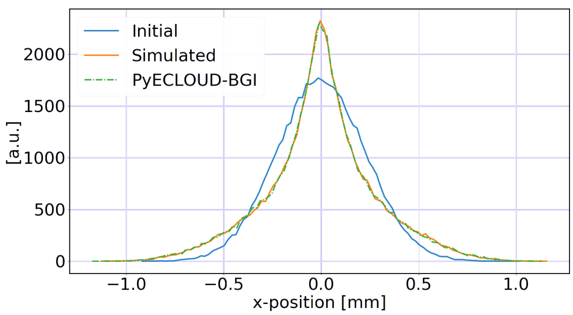

Figure 3: Comparison of simulated profiles with the PyECLOUD-BGI code for the LHC case (electron tracking).

COMPARISON WITH MEASUREMENTS

Measurements have been performed at the SIS-18 synchrotron in GSI with an electron detecting IPM equipped with an optical acquisition system at arbitrarily small extraction voltages in order to make a profile distortion visible. An ion detecting IPM with an electronic read-out system has been used in parallel in order to verify the actual beam profile. The measured ion profiles were fit with a Gaussian distribution (also because the actual profiles seemed to have tails) and were used as an input to the simulation. The parameters for the measurements are shown in Table 1 (SIS-18 case).

The result of the simulation compared to the measurements are shown in Fig. 4. The electron measurement shows a large broadening of the beam profile which is reproduced by the simulated profile. The deviation between measurement and simulation is ascribed to the effect of stray fields from neighboring magnets and to the inaccuracy of initial velocity generation under the assumption of a (atomic) Hydrogen target.

BIF SIMULATIONS

Simulations of Beam Induced Fluorescence monitors have been considered an important use case so in this section we show simulation results that were obtained for the more complex setup of foreseen HL-LHC electron lens diagnostics, based on BIF monitor and supersonic gas jet, with preliminary parameters [15].

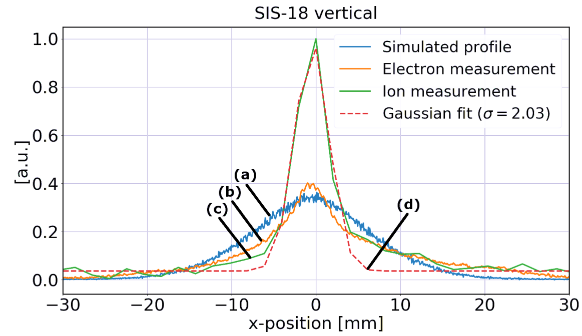

Figure 4: Profile measured at SIS-18 (vertical device) (b) compared to the result of the simulation (a). The profile of the ion-IPM (c) has been fit with a Gaussian distribution (d) in order to overcome the noise at the tails and to serve as a reference profile.

The parameters for the simulation are summarized in the following. The 7 TeV proton beam is represented by Gaussian bunches with 2.4 mm transverse FWHM (which corresponds to $\sigma_{x,y} = 1.02$ mm) and a length of $4\sigma_z = 1.25$ ns. Each bunch consists of 2.2×10^{11} protons and bunches arrive at a frequency of 40 MHz. The 10 keV electron beam is represented by a 5 A hollow DC beam with flat profile between inner radius of 1.2 mm and outer radius of 1.8 mm. The longitudinal electric field of the proton beam is neglected because of its highly relativistic energy. The magnetic fields of both beams are taken into account. An external solenoid field of $B_z = 4$ T (along the beam direction) is included. Excitation arises from the interaction of the beams with a transverse N_2 gas jet at 30 K temperature and with mean velocity $v_y = 800\,\mathrm{m\,s^{-1}}$. The relevant excited state $(N_2^+)^*_{391\,\mathrm{nm}}$ has a lifetime of 60 ns. For proton induced excitation the simulation was run for 420 ns in order to capture at least 99.9 % of all particles. Electron induced excitation was considered during the first 25 ns because after that period the situation repeats with respect to the electromagnetic fields.

The simulation performs discrete time steps of size Δt and the probability p_s that an excited state decays during a single step is constant during the simulation and can be determined as $p_s = 1 - \exp(-\lambda \Delta t)$ where λ is the decay rate of the excited state.

Figure 5 shows the one-dimensional projection (along y-direction) of the simulated profile of the proton beam. Most of the time the excited ions are subject to the electromagnetic field of the electron DC beam because of the short length of the proton beam ($4\sigma_z = 2.5$ ns). Together with the $B_z = 4$ T solenoid field the ions shift towards the center of the profile.

Figure 6 shows the simulated two-dimensional profile of the electron beam. The ions similarly move towards the center of the profile in the presence of the DC and the solenoid field. At $\sqrt{x^2 + y^2} = 1.2$ mm the attracting DC electric field drops to zero and below that boundary the ions are only subject to the opposite, repelling field from the proton beam. These counteracting effects lead to the ions accumulating in this region.

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The above results suggest possible difficulties when estimating the profiles of the proton and electron beam with the simulated BIF monitor.

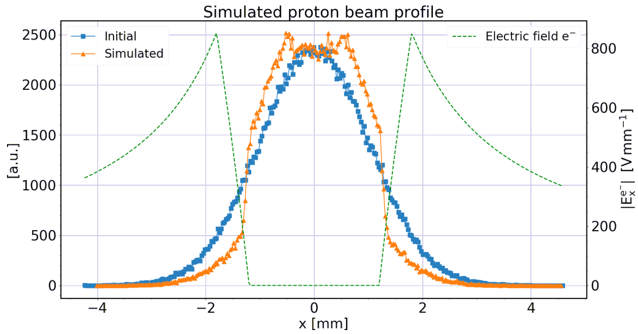

Figure 5: Simulated profile of the proton beam, integrated along y-direction. The bin size is 30 µm. The (radial) electric field of the DC electron beam is indicated (dashed line).

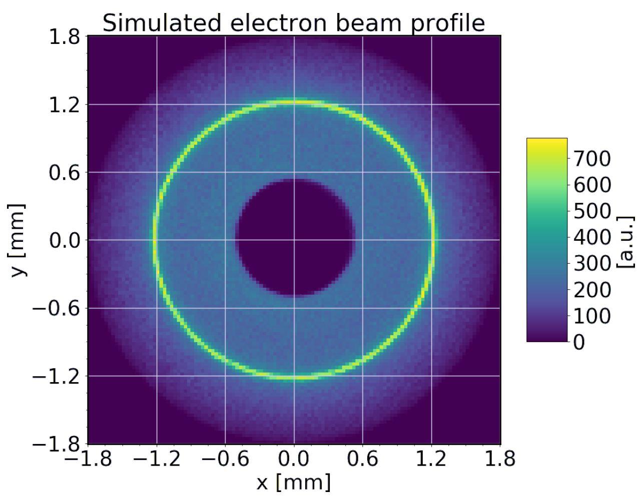

Figure 6: Simulated two-dimensional profile of the electron beam. The bin size is 30 µm. The original electron beam profile ranges from $\sqrt{x^2 + y^2} = 1.2$ mm to 1.8 mm.

SUMMARY

A new simulation tool – "Virtual-IPM" – has been established in order to combine various use cases, many of which have been realized already. It integrates numerous methods that are available in existing simulation codes and which have been benchmarked accordingly. The application includes a graphical user interface which facilitates the configuration of simulation cases. The code is publicly available as a git repository and is open for collaboration [16]. It includes a comprehensive documentation [17] and is available on the Python Package Index [18]. Future development of the application is already scheduled in order to include additional methods and use cases.

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