GAS SHEET DIAGNOSTICS USING PARTICLE IN CELL CODE

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Abstract

As intense particle beams propagate in dense plasma or gas, ionization effects play an important role in the particle dynamics. Due to Ammosov-Delone-Krainov (ADK) ionization mechanisms, plasma electrons are generated, causing different instabilities, and difficulties, in achieving overarching physics goals of wakefield accelerators. Advanced accelerator experimental tests with high energy, high charge, and low mm-mrad emittance beams, require sophisticated beam diagnostics. Here, we will discuss ADK ionization using the fully parallel PIC code `OSIRIS`. Specifically, we focus on investigation of gas sheet ionization diagnostics for characterizing high intensity charged particle beams. The behavior of the ionization contains critical information on the parameters of the drive beam, which are unveiled by using sophisticated reconstruction algorithms or a spatial imaging detector. For the gas sheet, a 150 µm wide gas sheet of uniform density is generated for ionization. We study the ion profile that was generated in order to reconstruct the driver beam transverse profile. In future work, we investigate a device to detect the photons from the gas recombination that is induced in the interaction.

INTRODUCTION

Beam diagnostics play a vital role in secure and reliable operations of any particle accelerator. For high energy beams at the Facility for Advanced Accelerator Experimental Test (FACET-II)[1], non-destructive beam profile monitoring is critical. There are several methods available to measure the beam profile but, due to the high intensity beams at FACET-II (see Table 1), a sophisticated method for effectively measuring bunch parameters prior to, or at, interaction points is needed. In this paper, we examine ADK ionization using the fully parallel PIC code `OSIRIS`. We focus on understanding ionization of a thin gas sheet. Detection of ionization in a gas sheet interacting with the driver electron beam using sensitive monitors allows for minimally invasive measurements of the ions. Gas sheet ionization diagnostics, either by tunnel ionization or ADK ionization, are prime methods available to provide real time spot size information for intense beams at focal points where other techniques are unfeasible.

INSTRUMENT OVERVIEW

The gas sheet ionization monitor is depicted in Fig. 1. The sophisticated imaging system consists of a high-pressure conical nozzle, shaping conical and rectangular skimmers, turbomolecular pumps for differential pumping, and an ion microscope (discussed in Ref. [2]). The gas jet generation and injection mechanism is relatively straightforward to implement compared to other complex injection schemes, such as optical or gas density down-ramp injections. The imaging system is based on an ion microscope subsystem, that is responsible for transporting, and imaging the ion beam that is generated at the gas sheet interaction region.

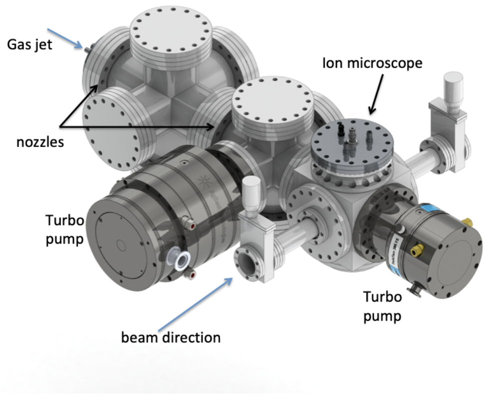

Figure 1: Gas sheet ionization monitor model. The system incorporates a series of skimmers and pumps to deliver a precision gas sheet at the interaction point.

The beam profile monitor under development is based on the experimental setup in Ref. [3]. The supersonic gas sheet, or gas curtain, enters the interaction chamber at a 45° orientation, where a beam of charged particles passes through the curtain perpendicular to its flow. The ions, and electrons, generated by the interaction between the neutral gas and the beam can then be detected using a dedicated imaging system to determine the transverse profile of the drive beam. Depending on the beam and gas sheet characteristics, transmission of ions varies from 50-100 percent for the range of interest. The primary factor in reduced transmission is the total charge of the ion beam, which increases space charge effects and drives expansion of the ion beam during transport. Simulations are used to generate training

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data from the `OSIRIS` or WARP codes, which is used to train the reconstruction model discussed in Ref. [4]. The reconstruction model outputs the original beam transverse profile.

METHOD

In order to gain better insight on the experimental results, we conducted 3D-PIC simulations using the `OSIRIS` code [5]. We chose `OSIRIS` based on its ability to handle highly nonlinear and kinetic processes that occur during high-intensity particle and laser interactions with the plasma, and to take advantage of its inbuilt ionization module for tracking generated ions. We ran simulations for the expected FACET-II beam parameters (Table 1) for a gas jet experiment, considering a netural gas with an electron beam charge of 0.5 nC. The simulation box size was 100 µm×60 µm×60 µm with a cell size of 100×100×100 and 8 macro-particles per cell. To resolve the injection processes, we needed time-resolved PIC simulations. Hence, simulations were chosen with a trade-off between propagation distance, resolution, and accuracy. The code used a moving window approach, where the simulation box moves at the speed of light, and the pulse is initialized near the leftmost edge of the window. Both the window and the pulse propagate rightward, and the window starts moving at the first time step of the simulation. `OSIRIS` also incorporates the ability to launch EM waves into the simulation, either by initializing the EM field of the simulation box accordingly, or by injecting them from the simulation boundaries. Mapping of trapped electrons and accelerating fields throughout the ionized gas was constantly simulated.

For the first scenario, we modeled a 10 GeV electron beam with a charge of 0.5 nC, σ_z = 14 µm, σ_x = 5 µm, σ_y = 7.5 µm, and captured the ionization process for high intensity beams that interact with the gas sheet. The gas sheet parameters were fixed at 150 µm thickness, and $1{\times}10^{20}$ m^{-3} density for this simulation. The resulting ionization distributions are plotted in Fig. 2. The ADK ionization was evident in the transverse structure of the ion cloud at the interaction region. Figure 3 shows the generated ion beam distribution at the interaction point. Ionization profile for a 0.5 nC bunch produces nearly 0.2 fC ion signal, but generates the expected annular distribution in the transverse plane. The total charge of the ion bunch in this case is very small. Collisions between like particles and between separate species tend to equilibrate the energy and distribution functions of the particles. Collisions were implemented using Monte Carlo collisions (MCC) package. For MCC the probability to ionize the gas is

$$P_i = n_g \sigma(V_i)|V_i|\delta t \tag{1}$$

Here, σ is gas cross-section, n_g is gas density, V_i is the velocity of the i^{th} incident particle.

Table 1: Parameters Used for the 3D-PIC Simulation

Parameter	Value	Unit
	Gas	
n_g	1×10^{14}	cm^{-3}
Sheet length	150	µm
	Drive Beam	
Q	0.5	nC
E	10	GeV
σ_x	5	µm
σ_y	7.5	µm
σ_z	14	µm
ϵ_{nx}	1	µm
ϵ_{ny}	1	µm

DISCUSSION

Techniques based on the interaction of electron beams and gas have been studied and tested successfully by several authors in order to characterize electron-beam cross sections relying on the space-charge field [6] of the electron beam. Ionization-based techniques and a high-peak electric field (tens of GV/m) associated with high-brightness electron beams have been used as methods for measuring the charge density. Relativistic electron beams with femtosecond or even attosecond durations and transverse beam sizes of micrometers or less carry radially polarized electric fields with tens of GV/m field strength. Such fields ionize a neutral gas through which the electron beam propagates. By detecting and characterizing the yield of ions, their kinetic energy distribution, or their spatial distribution, the electron beam can be characterized in space and time. In principle, the method may have a limited dynamic range in detectable field strength due to the limited number of electrons or ions a detector can measure. However, a significantly larger dynamic range can be obtained by using a mixed gas species or relying on modification of the kinetic energy spectrum of the ions in a preformed plasma (e.g., created using laser ionization).

We aim to produce an ion distribution which is small in size (sigmas are small) and compact in phase space. It is predicted that newly generated electrons and ions can be trapped by exciting the wake at the proper phase. In Fig. 4 we simulate a 3D case in which generated electrons are observed to gain more energy than background ionized gas electrons.

CONCLUSION

Installation of the setup will be performed at the FACET-II facility at SLAC National Accelerator Lab. Initially, the diagnostic will be tested at low beam charge and power to compare and benchmark against existing profile monitors. As FACET-II ramps up beam power capabilities, the testing of the gas sheet ionization diagnostic will also progress to higher beam powers, that would damage existing profile

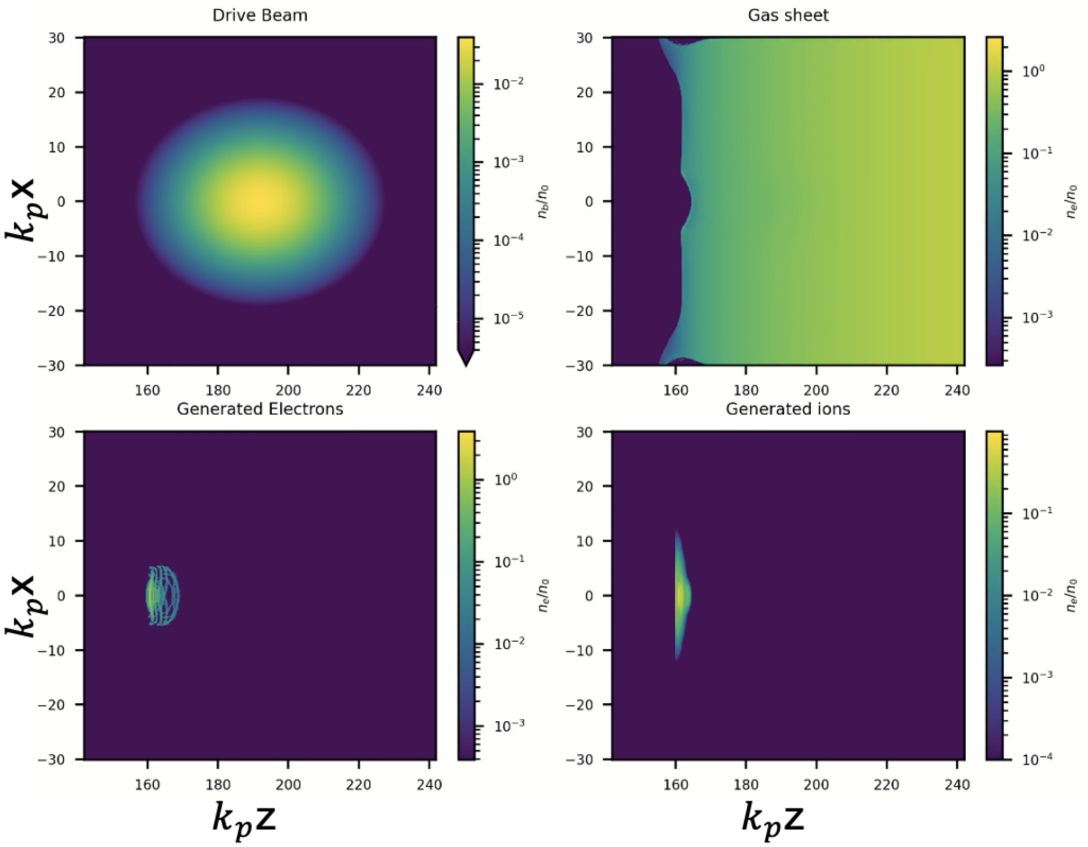
Drive Beam
Gas sheet
Generated Electrons
Generated ions

Figure 2: **Upper left:** The current model for the particle distribution is an artificially fiducialized test beam, **Upper right:** N2 gas sheet **lower left:** particle distribution shows the generated electron, **lower right:** shows the ion beam after it has traveled through the ion microscope

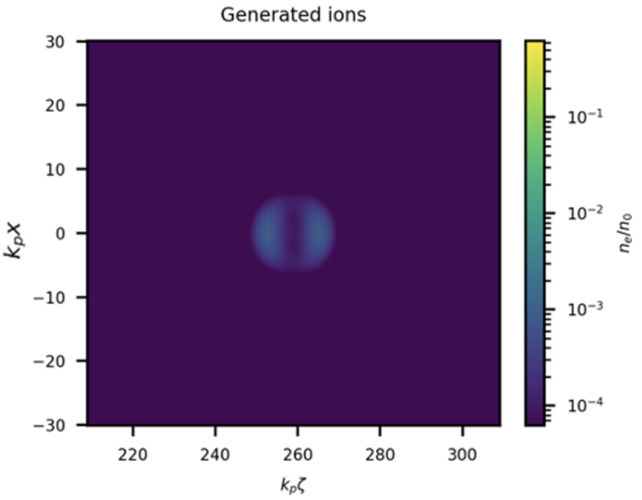
Generated ions

Figure 3: Generated ion beam distribution at the interaction point. Ionization profile for a 0.5 nC bunch produces nearly 0.2 fC ion signal, but generates the expected annular distribution in the transverse plane.

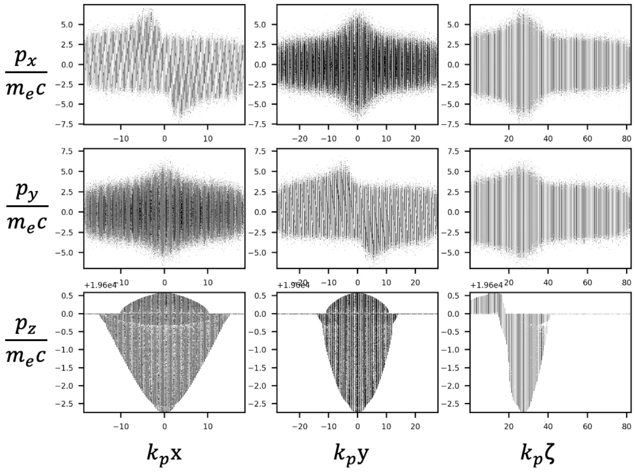

Figure 4: Phase space matrix of generated ion beam distribution at the interaction point.

monitoring technologies. The model shows that as electrons and ions are generated, they may be trapped in the wakefield and the newly created electrons can gain energy, as seen through ionization models using the OSIRIS particle-in-cell code. Tunneling ionization provides a unique signature of the incoming beam and can be implemented to uncover the transverse profile of beams at tight focus.

ACKNOWLEDGEMENT

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REFERENCES

[1] V. Yakimenko *et al.*, "Facet-ii facility for advanced accelerator experimental tests," *Phys. Rev. Accel. Beams*, vol. 22, no. 10, p. 101 301, 2019. `doi:10.1103/PhysRevAccelBeams.22.101301`

[2] N. Norvell *et al.*, "Gas sheet ionization diagnostic for high intensity electron beams," in *Proc. IPAC'21*, Campinas, SP, Brazil, 2021, paper MOPAB140, pp. 489–491. `doi:10.18429/JACoW-IPAC2021-MOPAB140`

[3] V. Tzoganis, H. D. Zhang, A. Jeff, and C. P. Welsch, "Design and first operation of a supersonic gas jet based beam profile monitor," *Phys. Rev. Accel. Beams*, vol. 20, no. 6, p. 062 801, 2017. `doi:10.1103/PhysRevAccelBeams.20.062801`

[4] N. M. Cook *et al.*, "Electron Beam Phase Space Reconstruction From a Gas Sheet Diagnostic," presented at the 13th International Particle Accelerator Conference (IPAC'22), Bangkok, Thailand, paper MOPOPT067, this conference.

[5] R. A. Fonseca *et al.*, "Osiris: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators," in *Computational Science — ICCS 2002*, 2002, pp. 342–351.

[6] R. Tarkeshian *et al.*, "Transverse space-charge field-induced plasma dynamics for ultraintense electron-beam characterization," *Phys. Rev. X*, vol. 8, no. 2, p. 021 039, 2018. `doi:10.1103/PhysRevX.8.021039`