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Self-consistent simulations of heavy-ion beams interacting with electron-clouds ☆

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Abstract

Electron clouds and rising desorbed gas pressure limit the performance of many existing accelerators and, potentially, that of future accelerators including heavy-ion warm-dense matter and fusion drivers. For the latter, self-consistent simulation of the interaction of the heavy-ion beam(s) with the electron cloud is necessary. To this end, we have merged the two codes WARP (HIF accelerator code) and POSINST (high-energy e-cloud build-up code), and added modules for neutral gas molecule generation, gas ionization, and electron tracking algorithms in magnetic fields with large time steps. The new tool is being benchmarked against the High-Current Experiment (HCX) and good agreement has been achieved. The simulations have also aided diagnostic interpretation and have identified unanticipated physical processes. We present the "roadmap" describing the different modules and their interconnections, along with detailed comparisons with HCX experimental results, as well as a preliminary application to the modeling of electron clouds in the Large Hadron Collider.

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1. Introduction

The steadily increasing beam intensity required in operational and upcoming accelerators leads to growing concerns over the degradation of beam emittance due to electron-cloud effect and gas pressure rise [1], and is of particular importance for the high-intensity accelerators envisioned for Heavy Ion Inertial Fusion (HIF) drivers and Warm-Dense Matter (WDM) studies. Accurate prediction necessitates a detailed understanding of the physical processes at play with a quantification of the relative importance of various effects. To this end, we have undertaken the development of a new generation of computer simulation code in conjunction with detailed measurements from a small but heavily diagnosed dedicated experiment, for extensive benchmarking and code validation. We provide here a brief overview of the simulation code and the dedicated experiment, and present recent results, focusing on the dynamics of electrons in the magnetic quadrupole section of the High-Current Experiment (HCX) [2], and a preliminary application to the modeling of electron clouds in the Large Hadron Collider (LHC) [3].

2. The WARP/POSINST simulation package

The simulation tool is based on a merge of the Heavy Ion Fusion accelerator code WARP [4] and the High-Energy Physics electron cloud code POSINST [5,6],

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supplemented by additional modules for gas generation and ionization [7], as well as ion-induced electron emission from the Tech-X package TxPhysics [8]. The package allows for multi-dimensional (2-D or 3-D) modeling of a beam in an accelerator lattice and its interaction with electron clouds generated from photon-induced, ion-induced or electron-induced emission at walls, or from ionization of background and desorbed gas. The generation and tracking of all species (beams particles, ions, electrons, gas molecules) are performed in a self-consistent manner (the electron, ion and gas distributions can also be prescribed—if needed—for special study or convenience). The code runs in parallel and benefits from adaptive mesh refinement [9], particle sub-cycling [10] and a new "drift-Lorentz" particle mover for tracking charged particles in magnetic fields using large time steps [11,12]. These advanced numerical techniques allow for significant speed-up in computing time (orders of magnitude) relative to brute-force integration techniques, allowing for self-consistent simulations of electron-cloud effects and beam dynamics, which were out of reach with previously available tools.

2.1. The "roadmap"

We have established a list of different functional modules, and their inter-relationships, that are ultimately needed to reach self-consistency for the modeling of HIF beams with e-cloud and gas, and have summarized it in a block diagram (see Fig. 1). We can imagine this as a "roadmap" of a self-consistent modeling capability of electron-cloud effects. The central block of the roadmap is a self-consistent PIC module that follows the beam through an accelerator lattice with its self-field and images at the wall. Ions from the beam halo that strikes the wall can desorb neutrals and electrons that have enough time to reach the beam before the end of the pulse, and interact with it. The time-dependent motion of neutrals and electrons must therefore be tracked. The gas can be ionized by beam ions and electrons, leading to new electrons and ions that must be tracked as well. All these particles can hit the walls and produce more neutrals and electrons. Finally, beam ions can be reflected at the wall, and charge-exchange reactions can occur in the gas. More details on the analysis that led to the establishment of this roadmap can be found in Refs. [11–13,15].

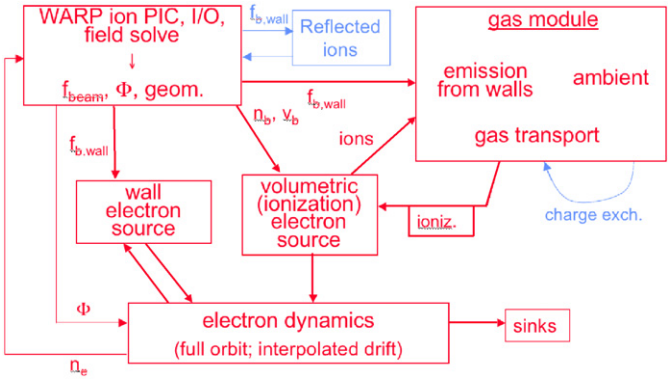

Fig. 1. "Roadmap" describing the different functional modules, and their inter-relationships, that are ultimately needed to reach self-consistency for the modeling of HIF beams with e-cloud and gas. At the time of this writing, most modules are operational, excepting the "reflected ions" and the "charge exchange" modules that are still being developed.

2.2. New features

We briefly describe here the features added to the WARP–POSINST capabilities. More detailed descriptions can be found in Refs. [7,11].

2.2.1. New interpolated mover

Self-consistent simulation of electrons and ions requires simulation of electrons in the quadrupole magnets as well as in the gaps between magnets, and running the simulation long enough to simulate the passage of the ion beam. This results in a broad range of time scales, ranging from the electron cyclotron period (10^{-11}–10^{-10} s) through the ion beam transit time (10^{-7}–10^{-5} s) through a fringe field or a series of lattice elements. The shortest electron cyclotron period is typically one to two orders of magnitude smaller than the next-smallest timescale, usually the electron bounce time in the combined beam-potential and magnetic wells. To deal with this large range of time scales in a unified manner, we have developed a mover for electrons that interpolates between full electron dynamics and drift kinetics (for more details, see Ref. [11]).

2.2.2. Gas module

Impact of energetic ions on surfaces can lead to desorption of neutral atoms or molecules. At high beam energies, characteristic of the HIF and HEP applications, electronic sputtering is the dominant mechanism. In this mechanism, the incident energetic ion transfers kinetic energy to the electrons in the vacuum chamber material, transporting, in turn, the energy to the surface and to the impurities adsorbed in the lattice. The desorption yield depends on energy and angle of impact, as well as material properties and surface history. Because the dependence of the yield is difficult to characterize for technical surfaces, in the model the yield at normal incidence is specified by a phenomenological quantity. The angular dependence of the yield is then characterized by the impact angle, conventionally measured from the surface normal. The enhancement of the yield at large angle (near grazing incidence) is possibly due to the enhanced backscatter of ions, as calculated by Molvik [13] using the SRIM code [14]. These backscattered ions result in an increase over the normal yield Y_0 by nearly a factor of 2 near grazing incidence,

$$\frac{Y(\theta)}{Y_0} = 1 + 1.82 \times 10^{-4} \exp(5.16\theta) \quad (1)$$

where θ is the angle of incidence measured in radians.