ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPME043

MODELING AND SIMULATION OF BEAM-INDUCED PLASMA IN MUON COOLING DEVICES

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Abstract

Understanding of the interaction of muon beams with plasma in muon cooling devices is important for the optimization of the muon cooling process. We have developed numerical algorithms and parallel software for self-consistent simulation of the plasma production and its interaction with particle beams and external fields. Simulations support the experimental program on the hydrogen gas filled RF cavities in the Mucool Test Area (MTA) at Fermilab. Computational algorithms are based on the electromagnetic particle-in-cell (PIC) code SPACE combined with a probabilistic, macroparticle-based implementation of atomic physics processes such as the absorption of the incident particles, ionization of the absorber material, and the generation and evolution of secondary particles in dense, neutral gas. In particular, we have proposed a novel algorithm for dealing with repetitive incident beam, enabling simulations of long time scale processes. Benchmarks and simulations of the experiments on gas-filled RF cavities and prediction for future experiments are discussed.

INTRODUCTION

A dense hydrogen gas filled RF cavity has been proposed for muon beam phase space cooling and acceleration. An important issue in high-pressure gas filled cavity is a RF power loading due to beam-induced plasma [1]. Incident particle beam interacts with dense hydrogen gas and causes significant ionization level. Due to high frequency of collisions with neutrals, electrons reach equilibrium within picosecond time scale and move by the instantaneous external electric field [1]. These charged particles, mainly electrons, absorb power of the electromagnetic field in the cavity. Thus subsequent bunch after the first one will experience a reduced external field [1,2]. This external field drop effect is strengthened by repetitive beam inflow. The recombination process mitigates the side effects of plasma loading. In order to promote the electron-capture process, electronegtive gas is used in cavity. This is the most critical process for the performance of the cooling device and should be modeled accurately in simulations. The aim of the current working simulation program is the development of mathematical and numerical models and parallel software for the simulation of processes occurring in gas-filled RF cavities.

A parallel electromagnetic PIC code with atomic physics, called SPACE [2], has been developed at Stony Brook University / BNL. It implements the finite difference time domain (FDTD) method and new mathematical models and numerical algorithms for the interaction of high-energy beams with neutral gas and plasmas. In particular, a novel algorithm dealing with repetitive beam is developed and implemented.

ATOMIC PHYSICS IN GAS-FILLED CAVITY

In this section, we describe the implementation of probabilistic models for atomic physics processes in gases under the influence of high energy particles and high gradient electromagnetic fields in SPACE. A macro-particle kinetic beam-plasma model is used to save the computing power. As each high energy macro-particle passes through the absorber, it ionizes the medium in real time and creates electron - ion pairs. The energy loss of the incident particle is described by the Bethe-Bloch formula [3]. The motion of ions and electrons is explicitly tracked described as the macro-particle plasma dynamics, and their atomic physics transformations are resolved as described below. For simplicity, the fast plasma formation and the plasma chemistry processes in pure hydrogen gas are investigated while the slow processes, i.e. the hydrogen recombination and the ion-ion neutralization are omitted in this analysis.

Ionization Process

We currently resolve the following processes that are most essential for the problem of interest:

$$p + H_2 \rightarrow p + {H_2}^+ + e^-, \quad (1)$$

$$e + H_2 \rightarrow {H_2}^+ + 2e^-, \quad (2)$$

$${H_2}^+ + H_2 \rightarrow {H_3}^+ + H. \quad (3)$$

The implementation using macroparticles is as follows. The energy loss of each incident charged macroparticle (it is proton for the MTA test) is calculated by the integration of the Bethe-Bloch formula along the particle trajectory

$$\Delta E = N_p \int f(v) ds \quad (4)$$

where f(v) denotes the energy loss rate described by the Bethe-Bloch formula as a function of the velocity of incident particle and N_p is the statistic weight of incident macro-particle. For convenience, N_H is defined as the statistic weight of electron-ion pair. Therefore, at each time step,

$$\left[\frac{\Delta E}{W\ N_H}\right]_{int} \quad (5)$$

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of electron-ion macro-particle pairs are created along the incident macro-particle path. Produced electron and positive ion macro-particles have random direction velocities corresponding to their initial energy. W is the average electron-ion pair production energy. The incident beam dominantly generates $H_2{}^+$ ion. Since it transforms into $H_3{}^+$ very quickly [4] the code uses $H_3{}^+$ ion instead of $H_2{}^+$ ion. So process (1) and (3) are implemented at the same time by above algorithm.

The Bethe-Bloch formula and W take into account the cascade process shown as the process (2). On the other hand, high energy secondary particles that are directly produced by the incident particles via the interaction with the beamline materials should be taken into account. The correction factor is provided [5] and involved in the simulation result.

Repetitive Beam Injection

The bunch spacing, the typical number of bunches, and the typical intensity per bunch in the MTA beam test are 5 ns, 2,000 and 10^9 protons/bunch, respectively while these in the nominal muon collider beam are 3.1 ns, 21, and 10^{12}, respectively. Since the hydrogen recombination time is typically 10 μsec order the number of electron-ion pairs grows exponentially. It is challenging in the development of PIC simulation because the code treats a very fast ionization process as well as other slow processes, e.g. beam structure, hydrogen recombination, ion-ion neutralization, diffusion, etc. In the previous PIC code, N_p and N_H were fixed. Consequently, the number of residual plasma macro-particles in the cavity after the last beam injection could be more than 10 times or 1000 times than that of first particle injection. We realize that this method is low efficiency with respect to the computing power. However, using variable N_p and N_H require a sort of neighbor search from an incident particle. As the number of particles increases, the code becomes slow, again.

In order to circumvent this problem, we have invented a new method to generate plasma particles in the ionization process. At the initial time, i.e. before the beam injection, macro-particles of plasma are distributed with 0 representing number. As the incident beam is passing through the cavity, it loses energy according to the Bethe-Bloch formula. This energy is distributed to the PIC mesh by an interpolation method used in PIC. This energy on mesh grids is then distributed to macro-particles of plasma by the interpolation method. The amount of energy at each macro-particles of plasma is used to increase its representing number. Since the presenting number can be real number, separation between integer and decimal is not necessary. This method is advantageous when recombination process is implemented because decreasing representing number is sufficient without deleting macro particles for secondary.

Drift of Charges in Cavity

After the ionization, ionizing electrons reach to equilibrium condition in a very short time because of their high collision frequency with dense gaseous hydrogen in the cavity. Thus, the energy spectra of plasma particles can be represented as the thermal distribution. The electron drift velocity is given by the ratio between gas pressure and the external electric field strength [2,6]. As a result, velocity of an electron in the code is defined by a drift velocity from past experiments [7].

Plasma Loading

Power dump in the cavity due to the beam-induced plasma load is estimated and compare with the MTA result [6] to benchmark the code. The implementation of a plasma loading at a time step into the code is

$$\mathrm{P} = \sum_i q_i \left(v_i{}^n \cdot E_{z_i}{}^n \right) = \sum_i q_i \frac{\left(z_i{}^{n+\frac{1}{2}} - z_i{}^{n-\frac{1}{2}} \right) E_{z_i}{}^n}{\Delta t} \quad (6)$$

where i and q_i denote the index of particles and charge of a plasma particle, respectively. Since a population of plasma macro-particle is time domain q_i should be updated at each time step.

The power delivered to gas in cavity is given by

$$\mathrm{P} = \frac{(V_{peak} - V)V}{R} - CV\frac{dV}{dt} \quad (7)$$

where R, C, and V_{peak} denote shunt impedance, capacity of the cavity, and the peak RF voltage, respectively [1,6]. R, C, and $E_{zi}{}^n$ are determined from the geometry of test cavity. Geometric corrections are given in refs. [1,6].

The mean RF power consumption per single plasma pair in one RF cycle dw [6] is computed by adding PΔt in Eq. 6 during one RF cycle and dividing it by the total number of plasma (real) particle pairs.

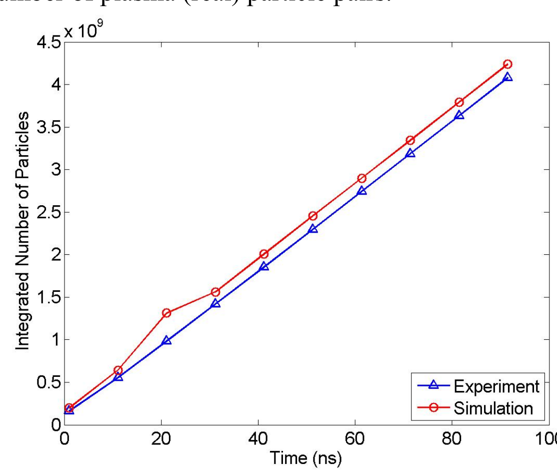

Figure 1: The number of proton injected into the cavity.

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RESULTS AND DISCUSSION

Simulations for Benchmark Test

We have performed simulations with physical parameters used in the MTA experiments [5]. Figure. 1 shows number of protons which have passed the cavity. The accumulated RF power loss is estimated by using eq. (6) and compared with the experimental result as shown in Fig. 2. The fraction in experiment is due to the measurement error. The voltage drop is also estimated from eq. (7) where P is evaluated from eq. (6) and compared with the experimental result as shown in Fig. 3. Figure. 4 shows experiment results and simulation results in various pressures. Simulations are consistent with the prediction well. The difference between the experimental data and prediction can be explained by the decrease of electron drift velocity in high pressure due to the multiple scattering [6].

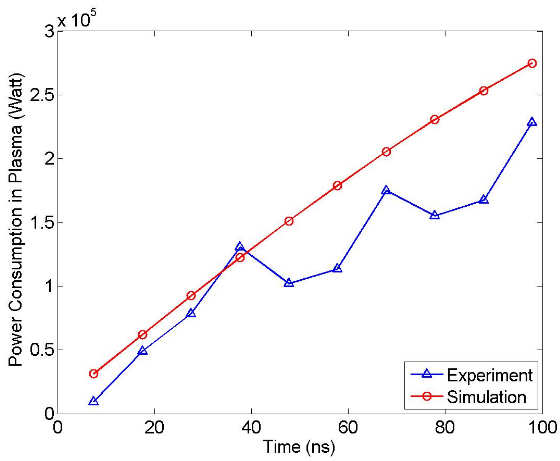

Figure 2: Average power consumption per one RF cycle in 100 atm.

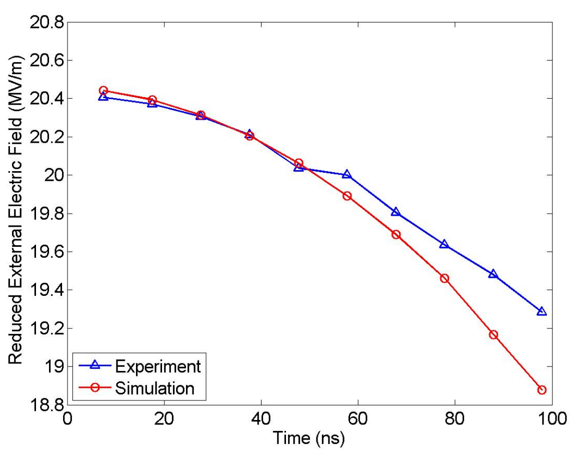

Figure 3: External electric field in the cavity in 100 atm.

Simulation of Muon Beam

We have performed a simulation with 200 MeV muon bunch of 5×10^{12} muon particles in 160 atm pressure and 5 cm cavity. In this simulation, we have got 3.5137e-17 J/cycle/pair *dw* value when 20 MV/m (650 MHz) external electric field is applied to the cavity. In order to get power consumption and external field decrease, additional simulations are required with specific cavity properties.

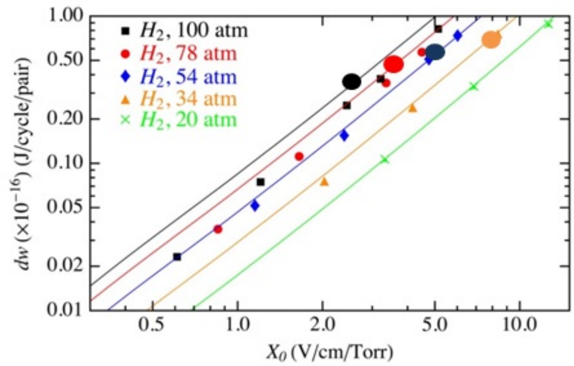

Figure 4: Plot of *dw* in various pressures. Thick circles are simulation results. Solid lines are theoretical computation and small plots are obtained by the experiment.

CONCLUSIONS AND FUTURE WORK

We have developed a parallel electromagnetic PIC code, SPACE, which includes atomic physics in high pressure gas-filled cavity. Simulations show results consistent with experiment up to about 100 ns. After 100 ns, recombination between ion and electrons in beam-induced plasma is significant. We are working on the implementation of recombination processes in order to simulate long time scale processes. We have also performed simulations with muon beam parameters and studied plasma loading effects under the high beam intensity.

ACKNOWLEDGEMENT

The research was supported in part by the DOE Muon Accelerator Program.

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