ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPMN015

SIMULATION OF BEAM-INDUCED PLASMA FOR THE MITIGATION OF BEAM-BEAM EFFECTS

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Abstract

One of the main challenges in the increase of luminosity of circular colliders is the control of the beam-beam effect. In the process of exploring beam-beam mitigation methods using plasma, we evaluated the possibility of plasma generation via ionization of neutral gas by proton beams, and performed highly resolved simulations of the beam-plasma interaction using SPACE, a 3D electromagnetic particle-in-cell code. The process of plasma generation is modelled using experimentally measured cross-section coefficients and a plasma recombination model that takes into account the presence of neutral gas and beam-induced electromagnetic fields. Numerically simulated plasma oscillations are consistent with theoretical analysis. In the beam-plasma interaction process, high-density neutral gas reduces the mean free path of plasma electrons and their acceleration. A numerical model for the drift speed as a limit of plasma electron velocity was developed. Simulations demonstrate a significant reduction of the beam electric field in the presence of plasma. Preliminary simulations using fully-ionized plasma have also been performed and compared with the case of beam-induced plasma.

PLASMA GENERATION

We study the process of plasma generation by the proton beam ionization of neutral matter, such as molecular hydrogen gas. We use the following parameters relevant to the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory.

Table 1: Proton Beam Structure

Energy	30 GeV
Normalized emittance	2e-6 m rad
Beta function	10 m
Number of protons per bunch	2e+11
Bunch duration	5 ns
Number of bunches	110
Bunch arrival interval	110 ns

Energy loss of an incident particle in matter by ionization is described by the Bethe-Bloch formula. But since the amount of energy absorbed by excitation processes is not precisely known, we use an empirical formula and experimentally measured ionization cross-sections. The evolution of the plasma density is given as

$$\frac{dn_e}{dt} = \frac{dN_p}{dt}\sigma L n_{gas} - \beta_r n_e n_i \qquad (1)$$

where dn_e/dt is the ionization rate, dN_p/dt is the inflow of protons in the elementary volume, L is the volume length, n_{gas}, n_e, and n_i are number densities of neutral gas, plasma electrons, and plasma ions, respectively, and β_r is the recombination coefficient. The ionization cross section σ of energetic particles in molecular hydrogen was experimentally measured in [1].

The recombination of plasma is strongly affected by the presence of neutral gas with much bigger density than the plasma density, and the electric field of the proton beam. The recombination coefficient is an empirical coefficient [2, 3] evaluated as

$$\beta_r = c_1 X^{-c_2}$$

Here $X = E/P$ is the ratio of electric field and hydrogen pressure, c_1 and c_2 are empirical numerical coefficients. We use results of measurements of plasma recombination in high-pressure hydrogen gas filled RF cavity at Fermilab [2, 3] to evaluate the recombination coefficient.

In the initial stage of plasma generation, recombination is negligible because of low plasma density, as shown in Figure 1. In this section, long-time evolution of plasma was obtained by numerically integrating equation (1). Fully resolved 3D PIC simulations are presented in the next section.

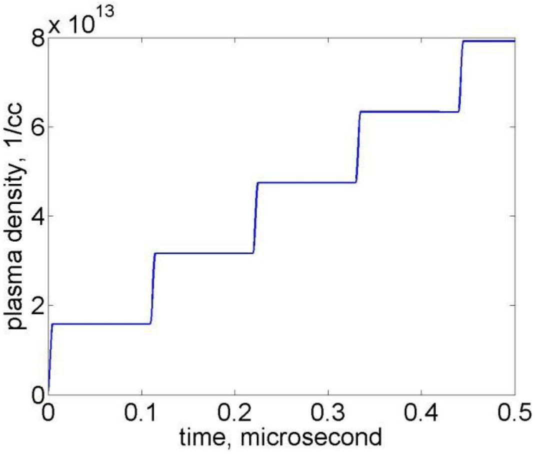

Figure 1: Plasma density evolution corresponding to first five bunches of proton beam.

As the plasma density increases, the recombination becomes more important. It balances the ionization and the plasma reaches a quasi-steady state with the number density of 2e+15 (1/cc), which is shown in Figure 2. The plasma is created by two proton beams propagating in opposite directions in neutral hydrogen gas with the density of 4e+18 (1/cc) and, at room temperature, the pressure of 0.16 bar. Such a plasma density is considered to be sufficient for the mitigation of beam-beam effects at certain conditions.

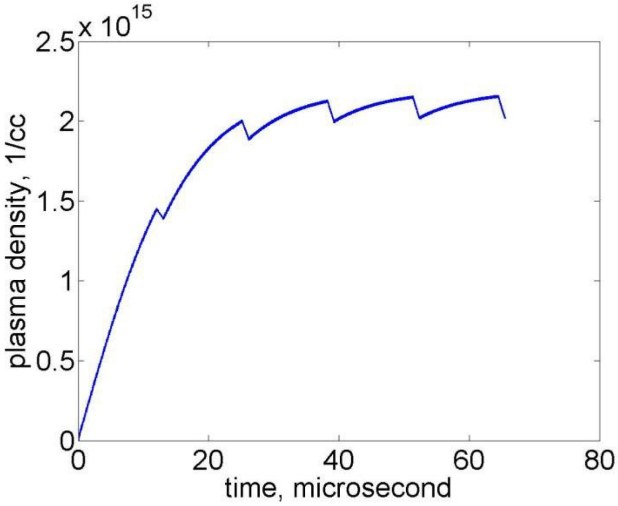

Figure 2: Evolution of plasma density created by proton ionization of neutral hydrogen.

BEAM-PLASMA INTERACTION

We have performed highly resolved numerical simulations to obtain details of plasma dynamics such as plasma oscillations, and the interaction of plasma with protons. The electromagnetic PIC code SPACE [4] was used for the direct numerical simulation of the plasma generation. The code SPACE is capable of simulation atomic physics processes such as ionization and recombination and has been used for the simulation of plasma generation by proton and muon beams in support of the Fermilab High Pressure RF cavity muon cooling experiments [5, 6].

In the direct numerical simulations of plasma generation during one proton beam using SPACE, our results, averaged over relevant time and length scales, agree with estimates in previous section.

The overall dynamics of the plasma number density is a relatively simple process that does not require highly resolved 3D numerical simulations. Using results of the previous section, we generate initial conditions that reproduce plasma in the saturation regime. In particular, the plasma distribution is computed according to the proton beam density distribution in the transverse plane.

The presence of neutral molecules reduces the mean free path of plasma electrons and reduces their acceleration. The drift speed is set as a limit of the velocity of plasma electrons to model the presence of high-density neutral gas. We have evaluated the dependence of the drift speed on the neutral gas density and electric field using theoretical analysis and experimental data [7]. The corresponding algorithm has been implemented in the code SPACE.

We simulate the pass-through of one proton bunch instead of a series of bunches, because this is sufficient to reproduce details of beam-plasma interaction. Longitudinal periodic boundary condition is used to model long proton bunches in a short computational domain.

Figure 3 shows the proton beam passing through the plasma, and the electric field around it. For clarity, plasma particles are not shown in the figure.

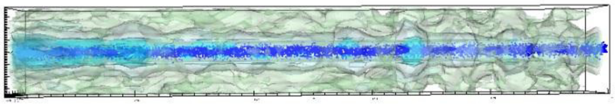

Figure 3: Protons and isosurfaces of the magnitude of the electric field in the plasma.

Our simulations demonstrate high-frequency plasma oscillation that agrees with theoretical estimates on plasma frequency. Plasma frequency can be computed as [8]

$$f = \frac{\omega}{2\pi}$$

$$\omega = \sqrt{n_e e^2 / m^* \epsilon_0} \qquad \text{(SI units)}$$

where n_e is number density of electrons, e is electric charge, m^* is effective mass of electron, and ϵ_0 is permittivity of free space. By computing numerical values of coefficients, the plasma frequency can be written as

$$f \approx 8980\sqrt{n_e}$$

The theoretical value of plasma frequency in our case is $f \approx 8.3e + 11$ (Hz) and $T = 1/f \approx 1.2e - 12$ (s).

To obtain the plasma oscillation frequency in simulations, we measure the longitudinal electric field at fixed point, and perform simulations with the numerical time step $dt \approx 1.0e - 15$ (s), which is much smaller than the theoretical value of plasma oscillation period. The numerical plasma oscillation period is $2e - 12$ (s), which is consistent with theoretical estimates. The small discrepancy could be attributed to errors in the distribution of plasma in transversal direction. The theoretical estimate assumes uniform distribution of the plasma, while our simulation uses normal distribution proton bunch which generates non-uniformly distributed plasma.

To show the mitigation effect of plasma, we compare the transversal electric field of proton beam in vacuum and in plasma. In Figure 4, the transversal electric field values are measured along the transverse coordinate in a selected cross-section.

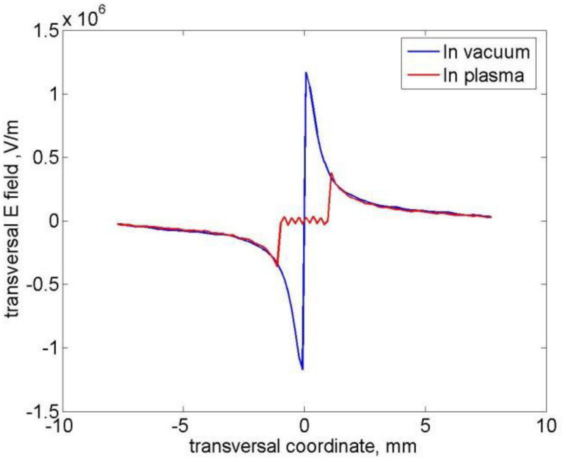

Figure 4: Comparison of electric field.

The comparison of electric field clearly shows the reduction effect around the center, in the region of high plasma density. Results for different cross-sections are consistent.

We compute the normalized 1-norm of the transverse electric field of the proton bunch in vacuum and in plasma, and average these values over time. Results are given in Table 2, which shows that the reduction factor is approximately 33.

Table 2: Averaged Electric Field

Proton beam in vacuum	5.12e+5 V/m
Proton beam in plasma	1.56e+4 V/m

For better explanation of the reduction of electric field, we analyze the motion of plasma particles, in particular the re-distribution of plasma electrons. In Figure 5, the difference between the final and initial distribution of the plasma electrons are shown in a selected slice. Figure shows the increase of the electron density in the center, caused by the attraction of the proton bunch.

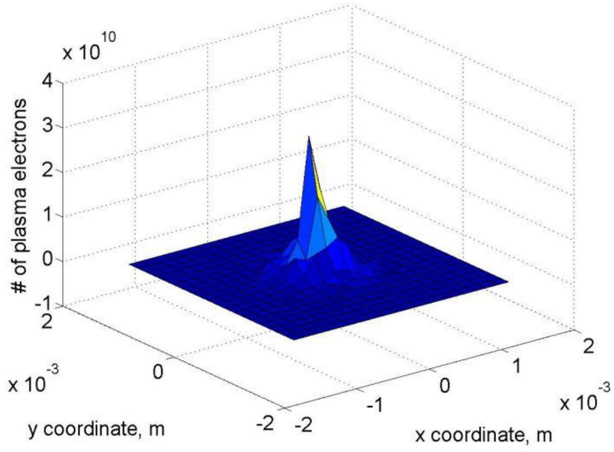

Figure 5: Re-distribution of plasma electrons.

Preliminary simulations using fully ionized plasma have also been performed, which differ from previous simulations by the absence of the drift speed limitation. Due to strong plasma oscillation, we used much lower plasma densities and observed smaller electric field reduction rates. The use of smoothing filter techniques was not sufficient to reach the desired plasma densities in the fully electromagnetic code. As a result, electrostatic simulations will be discussed in forthcoming work that regards the proton beam as a source of external current. Low velocity of plasma particles justifies the electrostatic approximation.

CONCLUSION

Numerical studies of the plasma generation by proton beams and the reduction of the beam electromagnetic field in the presence of plasma have been performed.

A 1D simulation was used to study the long time process of plasma generation by the proton beam ionization of neutral hydrogen gas. Highly-resolved 3D simulations using the electromagnetic PIC code SPACE have been performed to analyze details of plasma dynamics and the reduction of the beam electromagnetic field. The interaction of plasma with neutral gas was accounted by using electron drift velocity limitation.

Our results show that the plasma oscillation frequency is consistent with theoretical estimates. We have demonstrated strong reduction of the electric field caused by a re-distribution of plasma electrons towards the beam. The fully ionized plasma will be further studied in the future.

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