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INFLUENCE OF PLASMA LOADING IN A HYBRID MUON COOLING CHANNEL *

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Abstract

In a hybrid 6D cooling channel, cooling is accomplished by reducing the beam momentum through ionization energy loss in wedge absorbers and replenishing the momentum loss in the longitudinal direction with gas-filled rf cavities. While the gas acts as a buffer to prevent rf breakdown, gas ionization also occurs as the beam passes through the pressurized cavity. The resulting plasma may gain substantial energy from the rf electric field which it can transfer via collisions to the gas, an effect known as plasma loading. In this paper, we investigate the influence of plasma loading on the cooling performance of a rectilinear hybrid channel. With the aid of numerical simulations we examine the sensitivity in cooling performance and plasma loading to key parameters such as the rf gradient and gas pressure.

INTRODUCTION

A key challenge on producing intense muon beams is that they are created in a diffuse phase-space. As a result, the volume of the 6-Dimensional (6D) phase-space must be rapidly reduced via ionization cooling [1]. To reduce the transverse emittance, the beam is strongly focused with high magnetic fields and subsequently sent through an absorber material to reduce its overall momentum. Longitudinal emittance reduction is achieved by using wedge shaped absorbers and generating dispersion such that particles with higher energy pass through more material. In the aforementioned scheme, the cavities are filled with gas in order to prevent rf breakdown facilitated by multi-Tesla magnetic fields. Recently, a multi-stage tapered rectilinear channel capable for reducing the 6D emittance by at least five orders of magnitude has been designed and simulated [2, 3]. In that scheme the assumed gas pressure was 34 atm at room temperature.

An important issue in high-pressure gas filled cavities is rf power loading due to beam-induced plasma. Incident beam particles interact with dense hydrogen gas and cause significant amounts of ionization. Due to the high frequency of collisions with neutrals, electrons reach equilibrium within the picosecond time scale and move by the instantaneous external electric field. These charged particles, mainly electrons, absorb power from the electromagnetic field in the cavity. Thus subsequent beam bunches will experience a reduced electric field. This external field drop effect is reinforced by repetitive beam inflow. An experiment performed at the MuCool Test Area at Fermilab studied the formation of plasma created by a proton beam and its evolution over the course of many 805 MHz rf cycles [4]. In this paper, we investigate the influence of plasma loading on the cooling performance of a rectilinear hybrid channel.

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COOLING MUON BUNCHES

The cooling scheme we consider starts with the post-phase-rotation beam [5] that yields bunch trains of muons from which we use only 21 (see Fig. 1).

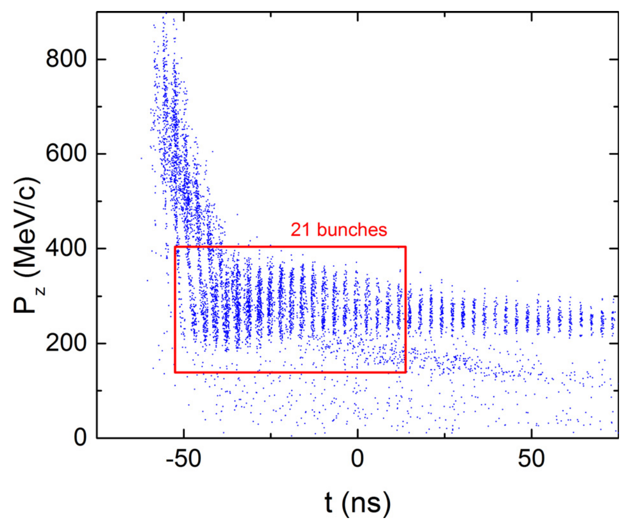

Figure 1: Longitudinal phase-space at the cooler entrance.

We consider a four-stage (A1-A4) tapered channel where each stage consists of a sequence of identical cells and the main lattice parameters are summarized in Tables 1 and 2. In all simulations the cavities are filled with gas at pressures of 34 or 100 atm at room temperature. The performance of the channel was simulated with the ICOOL code. The optimum performance for each pressure was found by using the conventional algorithm “Nelder-Mead” by scanning the rf phase, rf gradient, reference momentum, absorber length and wedge angle with the goal to maximize the beam luminosity within a given stage.

Table 1: Lattice Parameters for 34 atm

Stage	A1	A2	A3	A4
rf Freq. (MHz)	325	325	650	650
rf E (MV/m)	28.33	23.44	28.53	32.52
rf Phase (deg)	13.50	15.36	20.55	16.40
rf Length (m)	0.255	0.250	0.135	0.135

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Table 2: Lattice Parameters for 100 atm

Stage	A1	A2	A3	A4
rf Freq. (MHz)	325	325	650	650
rf E (MV/m)	28.88	22.44	28.73	33.90
rf Phase (deg)	13.46	15.22	21.03	17.26
rf Length (m)	0.255	0.250	0.135	0.135

THEORY OF PLASMA LOADING

The number of electron-ion pairs created by an incident beam in a gas filled rf cavity can be calculated:

$$N_p = N_b \frac{\frac{dE}{dx}\rho}{W_i} l \tag{1}$$

where N_b is the number of incident particles, dE/dx is the stopping power, ρ is the gas mass density, W_i is the average energy required to ionized a gas molecule, and l is the length of the cavity. For the scheme being considered here, hydrogen gas doped with 0.2% oxygen is used. The positive ions are therefore primarily large clusters of hydrogen (H_5^+ or larger).

The plasma generated by the beam acts as a resistive component and dissipates power from the rf cavity. The amount of energy dissipated can be estimated:

$$\begin{aligned} dw = \int P\,dt &= q \int v \left[\frac{E_0 \sin(\omega t)}{p}\right] E_0 \sin(\omega t)\,dt \\ &= q \int \mu \left[\frac{E_0 \sin(\omega t)}{p}\right] E_0^2 \sin^2(\omega t)\,dt \end{aligned} \tag{2}$$

where q is the particle's charge, v is the particle's drift velocity, E_0 is the electric field amplitude, p is the gas pressure, $\omega = 2\pi f$ is the rf frequency, μ is the particle's mobility, and the explicit dependence on E and p of the drift velocity and mobility have been shown.

There are three main processes in which the plasma may become neutralized. Electrons may recombine with hydrogen ions, and this process becomes faster at higher gas pressure and lower electric field. Electrons may become attached to oxygen molecules, which is a three-body process and requires an excited state of O_2^- to make a collision and de-excite. This process is therefore limited by the collision frequency of the gas. The attachment time decreases with increasing gas pressure and decreasing electric field. For the pressures considered here, the minimum attachment time will be on the order of 100 ps. Finally, hydrogen and oxygen ions may neutralize. This process is considerably slower than electron-hydrogen recombination or electron-oxygen attachment.

Rate equations for each of the charged particles can be written:

$$\begin{aligned} \frac{dn_e}{dt} &= \dot{N}_e - \textstyle\sum_k \beta_k\, n_e\, n_{H_k^+} - \frac{n_e}{\tau} \\ \frac{dn_{H^+}}{dt} &= \dot{N}_{H^+} - \textstyle\sum_k \beta_k\, n_e\, n_{H_k^+} - \sum_{k,l} \eta_{k,l}\, n_{H_k^+}\, n_{O_l^-} \\ \frac{dn_{O^-}}{dt} &= \frac{n_e}{\tau} - \textstyle\sum_{k,l} \eta_{k,l}\, n_{H_k^+}\, n_{O_l^-} \end{aligned} \tag{3}$$

where $\dot{N}$ is the production term, β is the electron-ion recombination rate, τ is the electron attachment time, η is the ion-ion neutralization rate, and the sums are taken over the existing ion species.

PLASMA LOADING ESTIMATION

An estimation of the plasma loading for the Hybrid Cooling Channel Stages A1 and A3 was calculated. The parameters used and assumptions made are as follows. The beam was bunched at 325 MHz, with 21 bunches, each assumed to be a delta function in time. A number of parameters were constant for both rf frequencies and gas pressures: the mobility for hydrogen ions was 9.6 $\frac{\text{cm}^2}{\text{V s}}$ and for oxygen ions 11.4 $\frac{\text{cm}^2}{\text{V s}}$; the neutralization rate of ions was 2×10^{-8} cm^3/s; and the minimum electron attachment time was 100 ps. Drift velocity measurements of electrons in hydrogen cited in Ref. [4] were used for 100 atm, while drift velocity measurements from Ref. [6] were used for 34 atm. Table 3 shows the additional parameters used.

Table 3: Plasma Loading Estimation Parameters

Frequency (MHz)	325		650	
Pressure (atm)	34	100	34	100
β (10^{-7} cm^3/s)	2	10	2	10
τ (ns)	6.81	0.769	6.81	0.769
Avg. mom. (MeV/c)	271	271	221.6	225.6
$\sigma_{trans.}$ (cm)	8.4	8.4	2.5	2.5

A recurrence table based on the rate equations of Eq. 3 was set up to track the number of each charged particle over the course of the beam pulse. The time step used was 1/1000 of an rf cycle. At each step the energy dissipated by each type of particle was calculated using Eq. 2. The total energy dissipated for the first 20 bunches was then summed to determined the plasma loading seen by the last bunch of the beam pulse. The goal was to study the effect of bunch intensity on the plasma loading in each cavity.

RESULTS

Examples of the results for the time evolution of electrons, hydrogen ions, and oxygen ions are shown in Figures 2, 3, and 4. The case shown represents a 325 MHz cavity filled with 34 atm gas with 10^{12} muons per bunch sent through.

It can be seen in Fig. 2 that when the electric field in the cavity passes through zero the number of electrons drops drastically.

In Fig. 3 the number of hydrogen ions builds with time, however as the density increases, the rate at which they neutralize also increases.

Unlike electrons and hydrogen ions, oxygen ions are produced continuously, as shown in Fig. 4, however sharp rises in their number can be seen whenever the electric field in the

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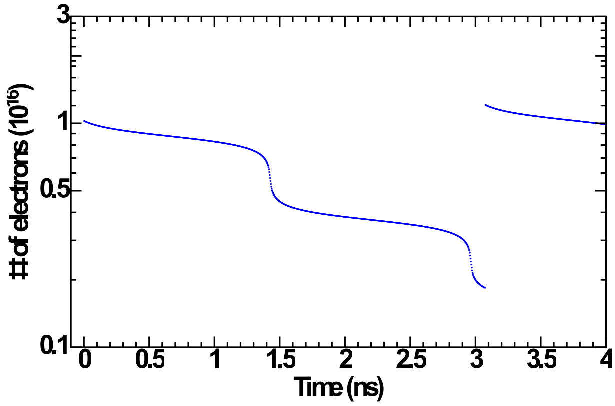

Figure 2: Number of electrons as a function of time for the first and beginning of the second bunch.

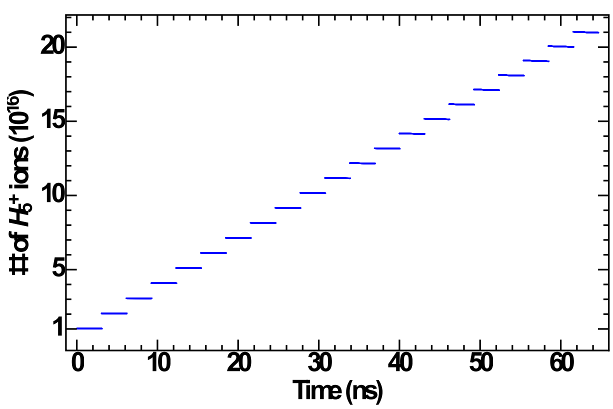

Figure 3: Number of hydrogen ions as a function of time for the entire beam pulse.

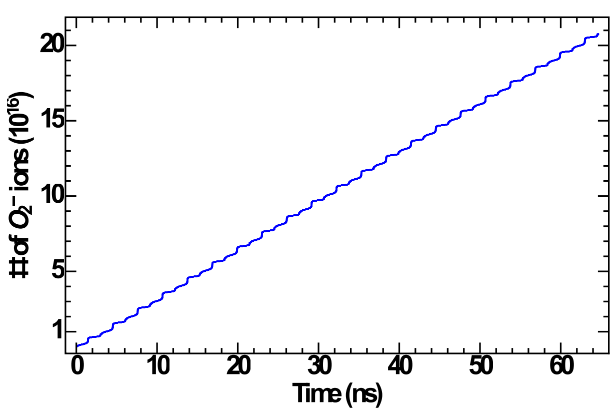

Figure 4: Number of oxygen ions as a function of time for the entire beam pulse.

cavity passes through zero, the opposite of that observed with electrons in Fig. 2.

Additionally, by the end of the beam pulse, significantly more ions exist within the cavity than electrons.

The results of the total plasma loading after the 20^{th} bunch as a function of number of muons per bunch are shown in Fig. 5.

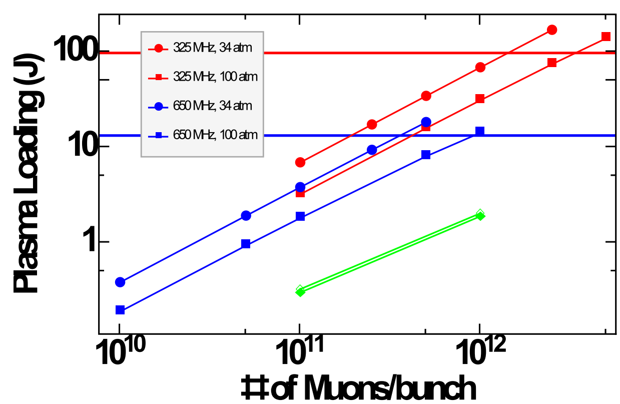

Figure 5: Total energy dissipated after the 20^{th} bunch has passed through the cavity as a function of number of muons per bunch. The horizontal lines are the stored energy of the 325 MHz cavity (red) and 650 MHz cavity (blue). The green diamonds are the results for the Helical Cooling Channel at 180 atm, described in Ref. [7].

CONCLUSION

The effect of plasma loading in a hybrid muon cooling channel is similar to that of beam loading in that the result is a degraded accelerating potential seen by later arriving bunches. In this respect, both plasma and beam loading must be accounted for in simulations of the emittance evolution of the beam. The results presented here indicate that plasma loading will completely degrade the accelerating potential seen by the last bunch at $1.4-3.4\times10^{12}$ muons per bunch for 325 MHz cavities, and $3.6-8.9\times10^{11}$ muons per bunch for 650 MHz cavities. These results will be combined with beam loading to simulate the cooling performance of they hybrid channel in future work.

The time scale for the cavity to fully recover is on the order of microseconds, and so for the 15 Hz repetition rate beam structure outline here, there would be no residual plasma by the time the next beam pulse enters the cavity.

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