HIGH PRESSURE GAS-FILLED RF CAVITIES FOR USE IN A MUON COOLING CHANNEL

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Abstract

A high pressure hydrogen gas-filled RF (HPRF) cavity can operate in the multi-Tesla magnetic fields required for a muon accelerator cooling channel. A beam test was performed at the Fermilab MuCool Test Area by sending a 400 MeV proton beam through an 805 MHz cavity and quantifying the effects of the resulting plasma within the cavity. The resulting energy loss per electron-ion pair produced has been measured at 10^{-18} to 10^{-16} J every RF cycle. Doping the hydrogen gas with oxygen greatly decreases the lifetime of an electron, thereby improving the performance of the HPRF cavity. Electron lifetimes as short as 1 ns have been measured, and electron-ion recombination rates are on the order of 10^{-6} cm^3/s. The recombination rate of positive and negative ions in the cavity has been measured on the order of 10^{-8} cm^3/s. Extrapolation in both gas pressure and beam intensity are required to obtain Muon Collider parameters, however the results indicate HPRF cavities can be used in a muon accelerator cooling channel.

INTRODUCTION

A recent White Paper submitted to the 2013 U.S. Community Summer Study of the Division of Particles and Fields by the U.S. Muon Accelerator Program (MAP) outlines a staged Muon Accelerator facility based at Fermilab [1]. The report outlines two main programs; a Neutrino Factory (NF), and a Muon Collider (MC). For the case of a MC, a Higgs Factory and multi-TeV collider are described. Because muons are created with a large initial phase space, the colliders requires significant (roughly six orders of magnitude) cooling.

The only cooling method that can work within the muon's lifetime is ionization cooling, and a so-called Helical Cooling Channel (HCC) has been proposed to do so [2]. The HCC is composed of normal conducting RF cavities arranged in a helix within a solenoidal magnetic field (see Fig. 1 & 2). The RF cavities are filled with a high pressure gas to allow operation in multi-Tesla magnetic fields. A series of six HCC cells, approximately 230 m long, reduces the 6D emittance by a factor of 175,000 [3].

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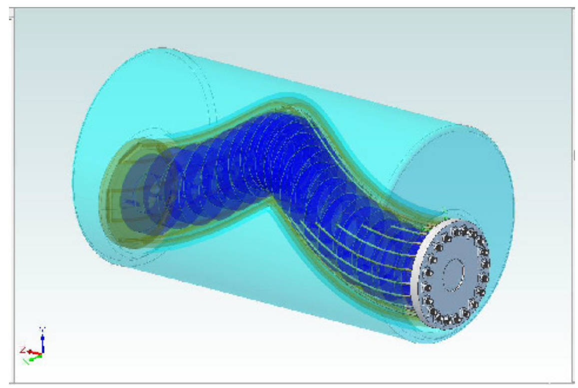

Figure 1: The 2D side view of one cell of the HCC, with components labeled. RF power is fed through the end. The solenoid coils are thermally isolated from the RF cavities [4].

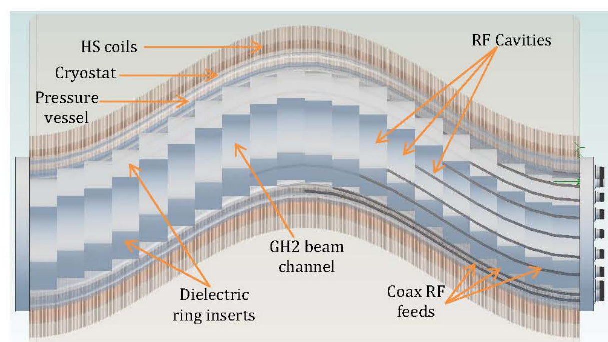

Figure 2: The 3D view of one cell of the HCC [4].

VALIDATION OF HIGH PRESSURE CAVITIES

A high pressure gas-filled RF (HPRF) cavity has been demonstrated to work in an external 3 T magnetic field without an ionizing beam [5, 6]. To validate its use in a HCC, a beam test using the 400 MeV Fermilab linac proton beam was performed at the MuCool Test Area (MTA). The cavity's performance using various beam intensities, gas pressures, dopant concentrations, and electric fields were studied with and without a 3 T magnetic field. Figure 3 shows a schematic of the experimental setup.

As the beam passes through the cavity, it ionizes the gas.

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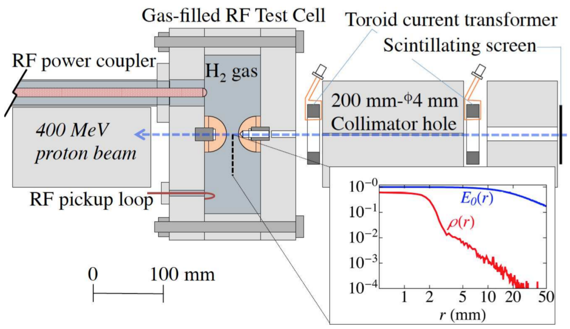

Figure 3: Schematic of the HPRF beam test setup. The beam enters from the right, passing through two collimators before impinging on the test cell. The inset plot shows the normalized electric field amplitude and simulated plasma density distribution as functions of radius.

The number of electron-ion pairs can be calculated:

$$N_{pairs} = \frac{\frac{dE}{dx}\,\rho\,L}{W_i} \tag{1}$$

where dE/dx is the stopping power, ρ is the gas density, L is the path length, and W_i is the average energy required to ionize a molecule.

Due to the high gas density, ionization electrons quickly come into equilibrium with the plasma, and drift with the cavity electric field. The electrons collide with gas molecules and transfer energy from the cavity to the plasma. The amount of energy transfered per charged particle can be evaluated by:

$$dw = q\int v\,E_0\,\sin(\omega\,t)\,dt \;=\; q\int \mu\,E_0^2\,\sin(\omega\,t)\,dt \tag{2}$$

where q is the charge of the particle, v is its drift velocity, E_0 is the amplitude of the electric field, and μ is the particle's mobility. The effect of the entire plasma is called plasma loading. To minimize the loading caused by electrons, an electronegative dopant gas can be used.

The results of the beam test are illustrated in Fig. 4 [7]. It can be seen that the addition of oxygen, present in dry air (DA), greatly decreases plasma loading. Additionally, there is very little difference between data taken with and without an external magnetic field.

The electric and magnetic fields inside the cavity as well as the ionization electrons' kinetic energy that would be present in a HCC were producible. However the maximum gas pressure was 100 atm while in a HCC it would be 180 atm. Additionally, the plasma density peaked at roughly 7×10^{11} cm^{-3} while in a real channel, due to the higher gas pressure and beam intensity, would be roughly 10^{16} cm^{-3}. Because of this, the results obtained in this beam test must be extrapolated to these higher densities.

The energy loss per particle, electron-ion and ion-ion recombination rates, and electron capture (by oxygen) time were measured as functions of electric field, gas pressure, and dopant concentration in order to extrapolate to the HCC parameters listed in Table 1.

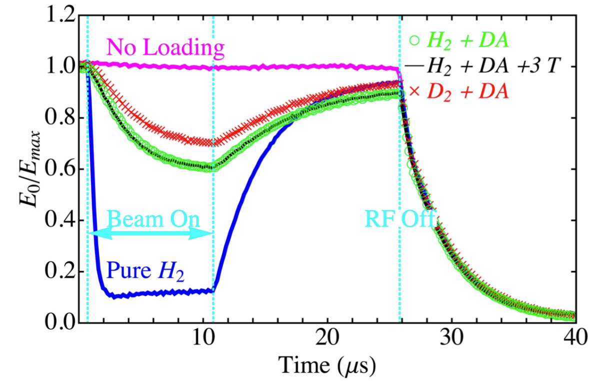

Figure 4: Typical RF envelopes recorded during the beam test. The beam is sent through the cavity once the flat top (E_{max}) has been reached. The magenta curve represents an RF pulse without beam.

Table 1: RF Parameters

Parameter	Unit	MTA Beam Test	HCC
RF frequency	MHz	801-808	325, 650
Gas pressure	atm	20-100	180
Oxygen conc.	%	2×10^{-4}-1	0.2
Peak E field	MV/m	5-50	20
External B field	T	0-3	4-14

Figure 5 shows the results of the electron attachment time, τ as a function of gas pressure. A fit to the data was used to extrapolate the time constant to 180 atm, which corresponds to 0.14 ns, indicated by the black lines on the plot.

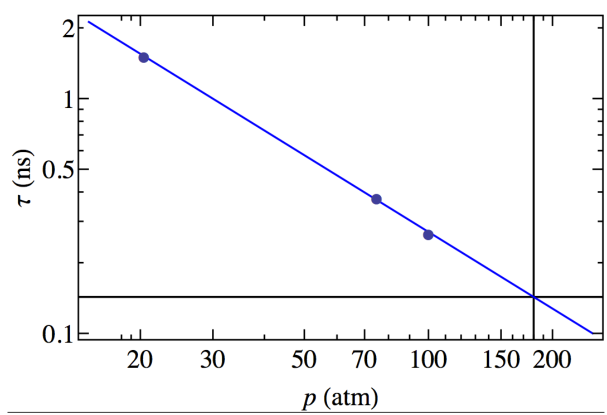

Figure 5: Electron attachment time as a function of gas pressure. The data (points) are taken from hydrogen gas doped with 1% DA (0.2% oxygen), and a fit was used to extrapolate the value of τ to 180 atm. The electron kinetic energy was kept constant at 0.4 eV.

PLASMA LOADING CALCULATION

A calculation of the plasma loading using muon accelerator beam and HCC RF parameters has been done. The beam parameters are given in Table 2. The beam bunches were assumed to be delta functions. The HPRF cavity's length was 10 cm and the stored energy was 19 J at 325 MHz and 4.7 J at 650 MHz.

The electron attachment time, electron-ion recombination rate, ion-ion recombination rate, and electron energy loss used in the calculation were based on extrapolations of measurements made at the MTA. The ion energy loss was based on classical values for the mobility.

Table 2: Beam Parameters

Parameter	Unit	Value
# of bunches	-	21
Bunch intensity	μ/bunch	10^{11}, 10^{12}
Bunch frequency	MHz	325
Injection phase	degrees	160

The results of the calculations are given in Table 3 & 4, for the two bunch intensities considered. Luminosity requirements dictate the bunch intensity before the final acceleration. To account for losses, the bunch intensity in the cooling channel will be between 10^{11} and 10^{12}.

Table 3: Plasma Loading Results for 10^{11} Muons per Bunch. The percent the accelerating voltage has dropped by the final bunch is given.

Parameter	Unit	325 MHz	650 MHz
Energy dissipated	J	0.292	0.317
% of total energy	-	1.5	6.7
% V_{accel} drop	-	0.8	3.4

Table 4: Plasma Loading Results for 10^{12} Muons per Bunch. The percent the accelerating voltage has dropped by the final bunch is given.

Parameter	Unit	325 MHz	650 MHz
Energy dissipated	J	1.84	1.98
% of total energy	-	9.7	42
% V_{accel} drops	-	5.0	24

It can be seen that, due to the larger stored energy, the 325 MHz cavity is only minimally loaded by the plasma, for either bunch intensity. The 650 MHz cavity experiences considerable plasma loading at the larger bunch intensity. This is due primarily to the buildup of ions over the course of the beam pulse. This is illustrated in Fig. 6. However, results obtained at the MTA indicate that the mobility of ions is smaller than the classical mobility, which was used here. This would have the effect of decreasing the loading due to ions.

CONCLUSIONS

The initial evidence suggests high pressure gas-filled cavities will work in a helical cooling channel for a muon

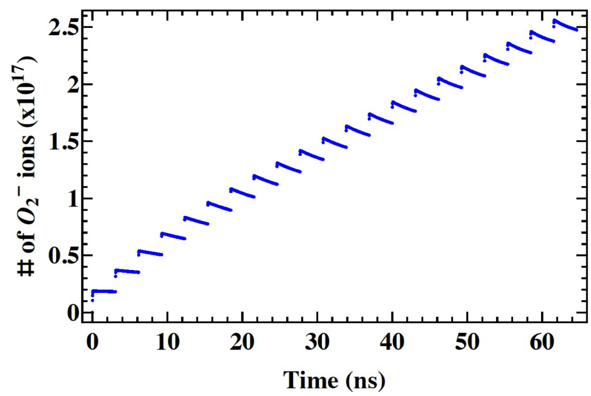

Figure 6: Number of O_2^- ions present in the cavity over the beam pulse.

accelerator. Extrapolation of parameters obtained at the MTA suggest that in the highest bunch intensity case, the accelerating gradient the final 10^{12} muon bunch would see would be degraded by 24%. The plasma dynamics inputs into this calculation were all taken to be conservative, and in reality the plasma loading should be less.

The effects of higher gas and plasma density must be considered, and simulations [8] are underway to address this. Evidence suggests that higher densities have a positive effect on the cavity's performance.

Additionally, wakefields and beam loading have not yet been considered. These are not issues unique to gas-filled cavities, and may be a serious consideration for $10^{11} - 10^{12}$ muons per bunch. The impact and mitigation are being investigated.

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