# $H_2$ Gas-filled RF Cavities and the Neutrino Factory Front End

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**Abstract.** RF breakdown has been observed in high gradient RF cavities within large magnet fields. Recent experiments and analyses also show that RF breakdown is suppressed in gas-filled RF cavities, but that large beam loading effects could occur. The front end of a neutrino factory or muon collider requires high gradient RF within magnetic fields and gas-filled RF cavities could avoid breakdown. Beam loading caused by secondary electrons produced within the gas by beam ionization can be very large. The effect at Front End parameters and its mitigation are discussed.

## INTRODUCTION

For the neutrino factory and the muon collider concepts, beam cooling systems have been developed that include high-gradient RF cavities and large magnetic fields.[1, 2] Experiments have shown that high-gradient RF can experience breakdown within large magnetic fields.[3] It has also been demonstrated that high-pressure hydrogen gas inhibits breakdown within high-gradient RF cavities with or without magnetic fields.[4] Tollestrup et al. have noted that operation of gas-filled RF with beam is complicated by the large number of electrons produced by ionization within the gas.[5] The electrons can oscillate coherently within the RF electric field, draining energy from the rf cavities. An initial experiment [6, 7] on a test cavity with beam showed beam loading effects qualitatively consistent with ref. [5].

The Neutrino Factory International Design Study (IDS) includes a "Front End", where pions from a production target are collected and captured and cooled as muons in a train of equal-energy bunches.[1] It requires relatively high-gradient rf cavities within relatively high-field solenoids. (The rf capture section use RF cavities of ~12MV/m gradients at ~200MHz within 1.5T solenoids and the cooling channel uses ~16MV/m gradient cavities within an ~±2.8T alternating-solenoid cooling channel.) In the present note we consider the use of gas-filled rf cavities in this system, discussing effects that can occur within the Tollestrup model, and compare with preliminary experimental results. Constraints on the use of gas-filled rf are presented and mitigation strategies such as electron-capture dopants are discussed.

## SCENARIO PARAMETERS

The beam loading effect depends critically upon the number and density of electrons produced within the rf cavity and that depends on the primary beam production intensity and scenario, as well as the gas-filled rf cavity parameters. For the present discussion, we follow the IDS report and accompanying reports which include several somewhat different scenarios, from which we will choose representative examples. The proton driver for the IDS will provide 4MW beam at 8GeV kinetic energy. Following a Project X based scenario [8], the protons would be formed into ~2ns-long bunches that hit the target at 60Hz (~$5.2\times10^{13}$/pulse). The π's from that collision would be captured by the front end transport and rf into a series of $\mu^+$ and $\mu^-$ bunches that would propagate through the cooling channel. As shown in fig. [1], one obtains ~35 $\mu^-$ bunches at 200 MHz spacing of varying intensity (with fewer muons toward later bunches), and one would also have a similar train of $\mu^+$ bunches. For a first estimate of the resulting secondary beam, we estimate that each proton would produce ~0.2μ and that these are split into ~25 bunches spaced by 5ns; in this model there would then be ~ $4.1\times10^{11}$ charges per bunch. This would approximate the charge density in the front of the bunch train and will be used in initial estimates of the effects of beam within gas-filled rf cavities. We label this the PD1 scenario.

Another proton driver scenario presented in the IDS would have an FFAG system cycling at 50Hz producing 3 bunches that would have ~$1.7\times10^{13}$/pulse.[1] The bunches would be separately targeted with ~20μs between pulses. Thus each pulse would produce a train of 25 bunches with ~$1.36\times10^{11}$ charges per bunch, which we label the PD2 scenario.

## Cooling Scenario Parameters

The muons travel through a cooling channel, such as that shown in Fig. 2. The channel is composed of 0.75m long cells, with each cell containing a 0.5m long cylindrical 200MHz rf cavity with ~16MV/m gradient, a focusing coil, and LiH absorbers. To prevent RF breakdown the rf cavities could be gas-filled with $H_2$. One option would be to include only sufficient gas to prevent breakdown;[9] this "low-pressure" (LP) option would require ~20 atm of $H_2$ (at standard temperature),which is a density of ~0.0018 gm/cm$^3$ A muon passing through the gas loses 4.2MeV/(gm/cm$^2$), and produces one ionization electron per 35 eV of energy loss. Thus a muon traversing the cavity would produce ~$10^4$ ionization electrons. As discussed below, energy loss of electrons in the ring depends on the Heylen parameter x,[10] which is expressed in the arcane units of V/cm/Torr, $x \cong 9.9$ for the LP case.

A second "high-pressure" (HP) option would be to have a gas pressure sufficient to provide all of the cooling energy loss. This would eliminate the need for LiH absorbers, and would have better cooling performance. The density required would be ~100atm, about 5 times more than the LP example. A muon traversing the rf cavity would produce ~$5\times10^4$ electrons. The HP example has a Heylen parameter of $x \cong 2.2$ V/cm/Torr.

## Electron Behavior in $H_2$

A muon beam passing through a gas-filled cavity produces a large number of secondary electrons, and the subsequent behavior of these electrons determines the rf constraints. Electrons within $H_2$ gas and electric fields have been studied and the behavior is discussed in ref. [10]. The observation is that free electrons have a large number of collisions with $H_2$ atoms forming into an electron cloud within the gas with an average electron velocity parallel to the electric field:

$$\vec{v}(x) = \mu_H(x)\vec{x}\cdot 5.9\times10^5\text{m/s}$$

where x = E/P is the electric field divided by the pressure, in the units V/cm/Torr, and $\mu_H(x)$ is the electron mobility factor, which is approximated by:

$$\mu_H(x) \cong 0.0172x^{-0.53}(1-0.024x^{0.71})^{-1.75}$$

Electrons extract energy from the rf cavity from $\vec{v}\cdot\vec{E}$ . The energy loss per rf cycle is estimated by Tollestrup et al.[5] to be:

$$\Delta E \cong \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e\mu_H(x\cos\theta)x\cos\theta\, 5.935\times10^5 E_{rf}\cos\theta d\theta\,/(\pi f_{RF})$$

$f_{RF}$ is the rf frequency and $E_{rf}$ is the cavity rf gradient. Note that the parameter $5.935\times10^5$ is simply the speed of a 1 eV electron. This energy loss per cycle per electron is then a simple function of x, $E_{rf}$ and $f_{rf}$.

Evaluating this expression for the examples of the front end, we obtain ~$2.6\times10^{-16}$ J for the LP example and ~$1.1\times10^{-16}$ J per electron per rf cycle for the HP example.

This model was initially based on observations of electrons in dc electric fields. Application to the rf cases requires the electron velocity to follow the oscillating rf fields, and significant mismatch in this will reduce the energy loss. Application over many rf cycles implies the electrons remain free electrons and do not combine with ions or molecules in the gas. This combination rate may depend critically on gas parameters and is not yet known for the present conditions. From general considerations, free electron lifetimes should be less than ~μs and greater than ns times. Within this range, we could have lifetimes less than an rf period (5ns) or lifetimes greater than the muon multi-bunch pulse length (~125ns), with greatly different implications for the rf scenarios.

## Evaluation at Front End parameters

The significance of the energy loss in the cavity due to electrons depends on a comparison with the energy stored in the rf cavity. This is estimated in a pill box model of the rf cavity as:

$$U_{cavity} = \pi\epsilon_0 \left(\frac{\lambda_{rf}}{2.61}\right)^2 \frac{0.518^2}{2} E_{rf}^2 L$$

where $\lambda_{rf}$ is the rf wavelength, and L is the cavity length. For the present example this obtains 158J for a 0.5 long 200 MHz cavity at 16 MV/m.

This energy within the cavity can be compared to the energy loss due to electrons. In the PD1 scenario, we obtain ~$4.16\times10^{11}$ charges per bunch, each of which produces $10^4$ electrons at LP parameters, which would have $2.6\times10^{-16}$ J of energy loss per rf cycle. This would become ~1.1J of energy loss in an rf cycle. In the HP scenario, this would increase to ~2.3J of energy loss. These are much smaller than the energy stored in the cavity and should be manageable with appropriate rf phase/energy controls.

However, if electrons do not recombine at the 5ns time scale but remain uncombined over the full pulse length of 25 bunches, then the beam loading effect becomes much larger. If no electrons recombine, we have ~$10^{17}$ electrons within the cavity, which would drain ~26J from the rf cavity in the LP case in the last bunch period (and ~60J in the HP case). Integrating over the bunch train would deplete the cavity, and it would be difficult to manage the rf power to compensate for this.

One can do the same calculation for the lower peak-power version of the proton driver (PD2), where the energy losses are a factor of 3 less. In that case the energy loss from a single bunch would be more easily managed, and energy losses from a bunch train without recombination would be difficult to manage but parameters are closer to making this possible.

## Comments on Electron Recombination

From the previous discussion, we note that use of gas-filled rf within the Neutrino Factory becomes difficult if electrons produced by ionizing beam do not recombine, and the electron velocities within the gas continue to oscillate in phase with the RF field oscillation. If the recombination time is reduced to ~10 ns or less the energy loss within the rf cavities would be manageable. That recombination time depends on the density of secondary ions produced in the rf cavity and is difficult to estimate. The time is expected to be much shorter in high density gas, which would favor the use of the HP scenario.

The combination time can be greatly reduced by the addition of a small amount of electronegative gas. Electronegative molecules attract free electrons, readily forming negative ions. In the MTA experiment a small amount of $SF_6$ gas (at 0.01% density) greatly reduced free electron lifetimes.[7] Fig. 4

shows some preliminary experimental results indicating that free electron lifetimes are reduced to a few ns. $N_2$ gas can also be used, but $N_2$ is relatively inert and does not easily attract electrons.

In a final system design $SF_6$ would not be desirable because the cavities could be damaged by Sulfur deposits, and $SF_6$ freezes at lower temperatures. However, $O_2$ has similar electronegativity, and relatively benign chemical byproducts ($H_2O$). One must design a system that will convince a safety committee that $O_2$ density will remain small.

## SUMMARY

Following analyses previously presented by Tollestrup et al.[5] we have considered the use of gas-filled rf within the Neutrino Factory Front End. Gas-filled rf will prevent cavity breakdown within magnetic fields. However that use of gas-filled rf within the Neutrino Factory becomes difficult if electrons produced by ionizing beam do not recombine, and their velocities within the gas oscillate in phase with the RF field oscillation. This problem is mitigated if recombination occur within the required time, and it appears that an addition of a small amount of electronegative gas may insure that recombination. More analysis and experiments specific to Neutrino Factory parameters (200MHz) should be developed to confirm this, and complete system design, including rf compensation from electron-induced beam loading, will be needed to insure implementation of gas-filled rf within the front end cooling channel.

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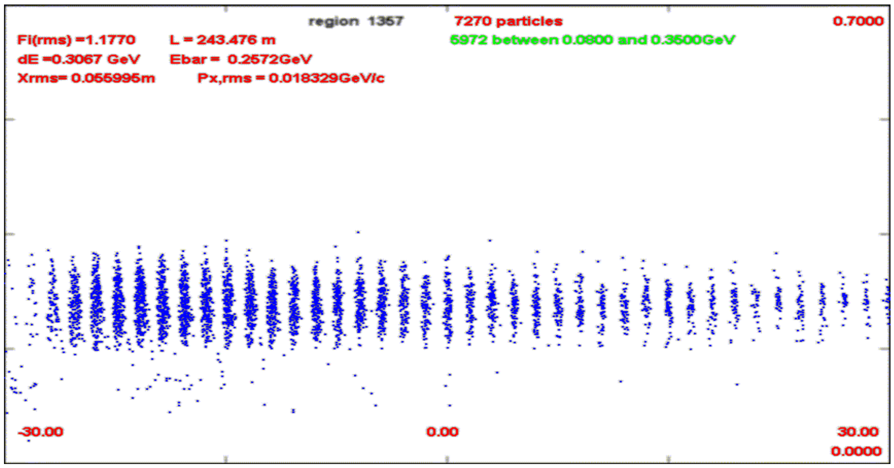


**FIGURE 1.** Momentum-time distribution of muon beam in the IDS cooling channel, as produced in an ICOOL simulation. The muons are formed into a string of muon bunches ($\mu^-$ are blue). Only $\mu^-$ are shown; there is also a similar train of $\mu^+$.

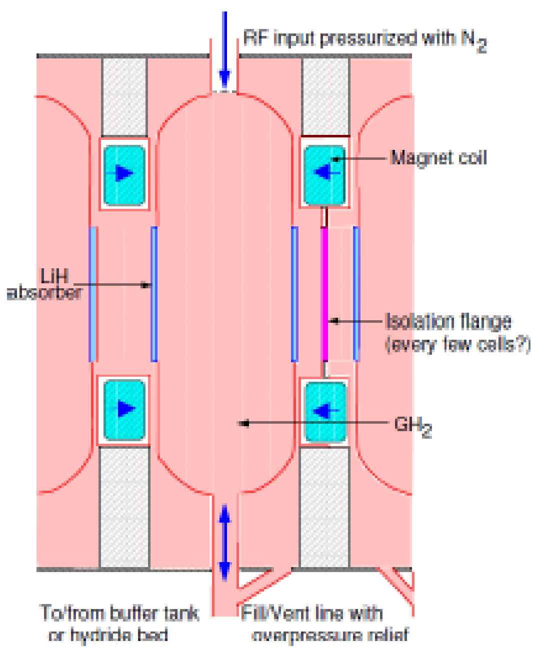


**FIGURE 2.** Sketch of a cooling cell with rf cavities, magnetic focusing coils and Momentum-time distribution of muon beam in the IDS cooling channel, cooling as produced in an ICOOL simulation.

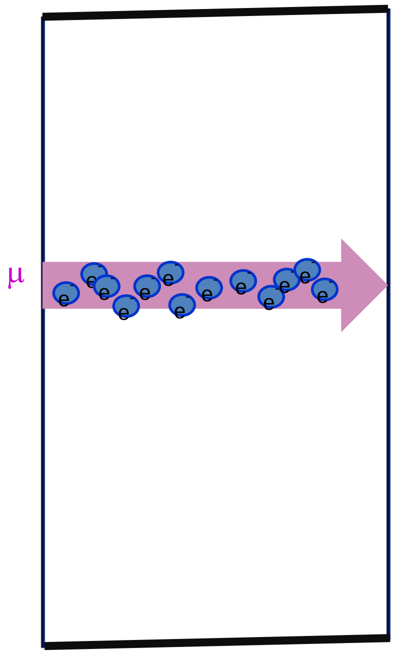


**FIGURE 3.** Sketch of a μ beam passing through an rf cavity, producing a trail of electrons.

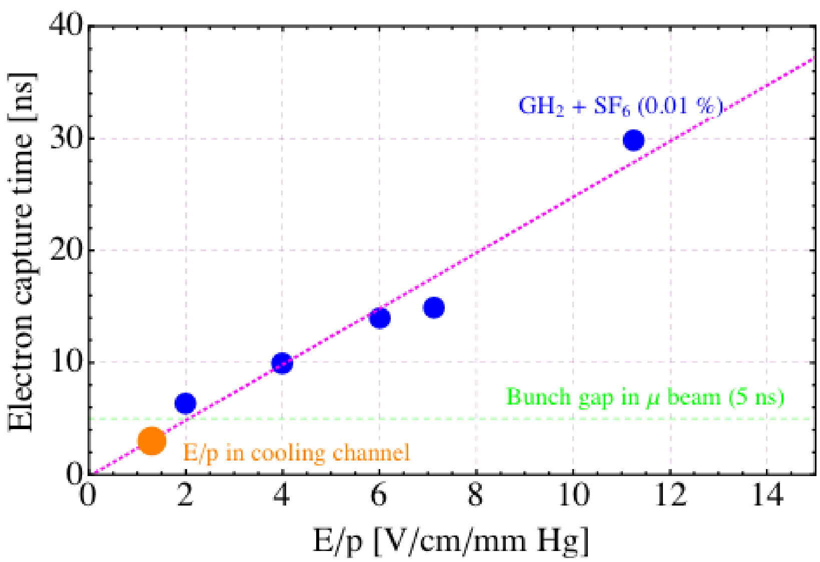


**FIGURE 4.** Electron lifetime as a function of x=E/P in $H_2$ gas with a small amount of electronegative $SF_6$ gas (preliminary data).[11]

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