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# UTILIZING GAS FILLED CAVITIES FOR THE GENERATION OF AN INTENSE MUON SOURCE*

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*Abstract*

A key requirement for designing intense muon sources is operating rf cavities in multi-tesla magnetic fields. Recently, a proof-of-principle experiment demonstrated that an rf cavity filed with high pressure hydrogen gas could meet this goal. In this study, rigorous simulation is used to design and evaluate the performance of an intense muon source with gas filled cavities. We present a new lattice design and compare our results with conventional schemes. We detail the influence of gas pressure on the muon production rate.

## INTRODUCTION

The relative immunity of muons to synchrotron radiation due to their large rest mass suggests that they may be used in place of electrons for fundamental high-energy physics research [1] as well as for various industrial and medical applications. However, the short lifetime of muons (2.2 μs in the rest frame) makes a muon beam very challenging technologically. Muons can be produced indirectly through pion decay by interaction of a multi-GeV, high-power (1-4 MW) proton beam with a stationary target. The muon yield is fractionally small, with large angle and energy dispersion. In this paper the production of pions, their decay into muons and the survival of muons during transport is studied.

## MUON CAPTURE CHALLENGES

A key requirement in producing an intense muon source is that the phase space-volume of the produced beams must match the acceptance criteria of the downstream accelerators. This demands a front-end channel (the part of the facility between the target and the first linear accelerator) for manipulating the beam in transverse and longitudinal phase-space [2]. For the latter, a series of rf cavities form the resulting muon beam into strings of bunches with different energies, and then align them into nearly equal central energies by phase-rotating the beam. To reduce the volume of transverse phase-space, the bunches pass through a cooling channel, which reduces the beam's emittance using ionization cooling. The cooling channel consists of absorbers, which lower the transverse and longitudinal momentum of beam particles, and rf cavities, which restore the particle's longitudinal momentum, inside a magnetic channel. A common feature of the front-end lattices is that it requires the rf cavities to operate within strong magnetic fields that focus the muons.

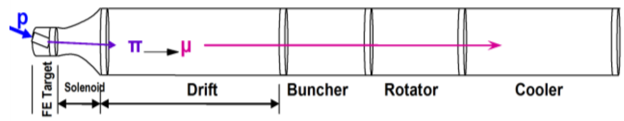


Figure 1: Schematic of the muon capture channel.

There are challenges in operating rf cavities in magnetic fields [3]. For instance, typical rf gradients in the cooling channel are 20-25 MV/m, while the magnetic field is near 2 T. Experimental and numerical studies indicated that this configuration enhances the possibility of rf breakdown. The use of rf cavities filled with high pressure hydrogen gas was proposed to overcome this difficulty. The gas not only provides the necessary momentum loss as a cooling material but also increases the breakdown gradient of the cavity. Experiments [4] have demonstrated that a breakdown gradient of 65.5 MV/m could be achieved in a 3 T magnetic field with 70 atm hydrogen gas. Here we investigate a muon capture channel which utilizes gas filled cavities and compare it's performance against the conventional vacuum channel. We examine the performance for two different pressures: One at 34 atm and one at 100 atm, both at room temperature.

## SYSTEM OVERVIEW

As shown in Fig. 1, a 1 MW proton driver produces bunches with 6.75 GeV in energy. The beam is directed onto a carbon (C) target enclosed in a 20 T solenoid. The pions created are captured as they transverse a ~5 m long, tapered superconducting solenoidal magnet system, where the field profile drops adiabatically from 20 T to 2.0 T. This is followed by a drift section with a constant 2.0 T field, where the pions decay into muons, and the beam develops a time-energy correlation with a high-energy "head" and a low-energy "tail". Then the beam is bunched into a string of bunches in a "buncher" followed by "phi-E" rotator section that aligns the muon bunches to nearly equal energies (matched at 325 MHz spacing) and then cooled in 325 MHz cooling channel with LiH absorbers.

In the buncher the frequency declines along its length from cavity to cavity, starting from 490 MHz at the entrance and dropping to 365 MHz at the exit. The rf gradient gradually increases from 0 to 15 MV/m using the relation $15z/L_B$, where $L_B$ is the buncher length. In the cooling channel the frequency further decreases from 364 to 326 MHz but the gradient remains fixed at 20 MV/m.

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Both buncher and rotator are within a constant 2 T magnetic field. Finally the cooler requires 25 MV/m, 325 MHz rf within an alternating solenoidal focusing lattice (the central field flips between +2.8 T to -2.8 T from cell to cell). The baseline cooling cell is 75 cm long and contains two 1.5 cm thick LiH absorbers. The overall performance is shown in Fig. 2. For 6.75 GeV protons on a C target the muon per proton rate for positive and negative muons is 0.0613 and 0.0481, respectively. In these simulations, the initial π/μ production on the target was generated using the MARS 15 program [5] and tracked through the front-end channel with ICOOL; μ's within the reference acceptances ($A_t$ <0.03m, $A_L$ < 0.25m) contribute to μ/p. The $\mu^+$/p from 6.75 GeV p on C target is used as the reference beam [6]. The μ/p are somewhat less than the results for 8 GeV protons on a Hg target. We note that in the MARS particle production we assume the default IQGSM=1 for the event generator parameters for nuclear inelastic interactions.

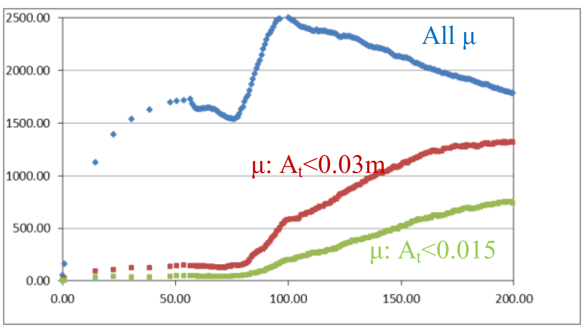


Figure 2: Baseline performance for positive muons on a muon capture channel with gas-free rf cavities.

## GAS FILLED MUON CAPTURE

The principle for the gas filled system is illustrated in Fig. 3 for the buncher/rotator system and the cooler. In a standard gas filled cooling channel the energy loss is distributed throughout the channel, rather than localized at discrete absorbers. One challenge is that such a system requires high pressure (density corresponding to ~160 atm at room T). For the cooling system, we have proposed [7] an alternative, where we use a minimum value of gas sufficient enough to protect the rf from breakdown while the majority of cooling is still done with LiH.

Table 1: Baseline parameters for an intense muon source that use gas free cavities. Note that there are no cavities in the drift section.

| Section | Length | rf frequencies | rf gradient |
|---|---|---|---|
| Drift | 57 m | - | - |
| Buncher | 21 m | 490→365 MHz | 0-15 MV/m |
| Rotator | 24 m | 364→326 MHz | 20 MV/m |
| Cooler | 80 m | 325 MHz | 25 MV/m |

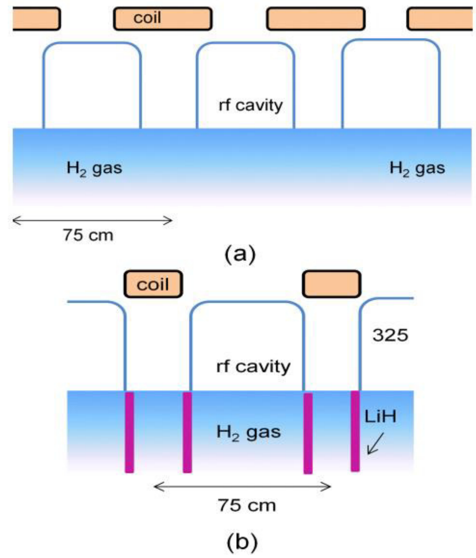


Figure 3: Gas filled scheme: (a) Buncher and phase rotator section, (b) cooler section.

As further configuration we propose using gas filled cavities in the phase rotator and buncher sections. Again, the gas could suppress breakdown, enabling a higher gradient, and the gas provides energy-loss cooling. Below we examine two cases: (a) one with gas density at 34 atm and (b) at 100 atm ($H_2$ at 293° K).

The gas adds dE/ds energy loss to the muons passing through the buncher and rotator, as well as multiple scattering. The energy loss from the gas is ~1.14 MV/m at 34 atm and 3.5 MV/m at 100 atm. To recover performance similar to or better than the gas-free case, this energy loss must be compensated by adding more rf gradient for acceleration and bunching.

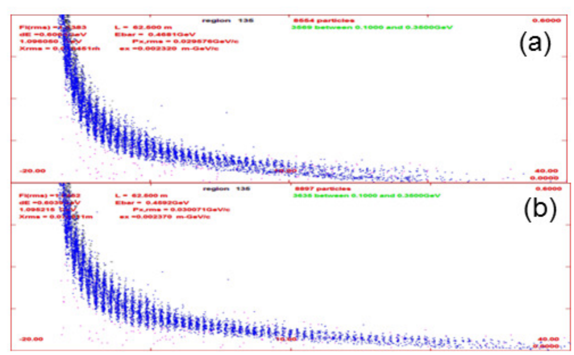


Figure 4: μ bunch trains at 72 m from target, after initial bunching: (a) with 34 atm in buncher and rotator; and (b) with 17 atm in buncher. With the larger density, low energy muons are lost and the bunch train is shorter.

### *Results for Low Pressure (34 atm)*

The target and drift sections remain similar to the baseline case. Initially 34 atm (0.00285 gm/cc) is used for both buncher and rotator. If rf voltages are maintained at baseline, μ/p drops to ~0.050 (~17% less). If the rf gradients are increased to 20/25/28 for buncher/ rotator/

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cooler, respectively, μ/p increases to ~0.058, close to the baseline performance.

Much of the loss occurs at the beginning of the buncher section where the rf gradient is relatively low and the gas based energy loss is relatively large. The original beam covers all phases but the capture buckets do not, since they now require stable acceleration to offset the energy loss in gas. Low energy muons with a larger dE/dx are lost, and the bunch train is shortened; the trailing bunches formed from low energy muons are lost (these lower intensity bunches are not retained in a collider scenario.)

Reduction of the gas density in the buncher to 17 atm improves μ/p to ~0.065, slightly better than baseline.

### *Results for High Pressure (100 atm)*

An increase in density in the rotator to 100 atm (0.084gm/cc) would increase the amount of cooling in the rotator, and give added margin in avoiding breakdown.

Increasing to 100 atm while keeping gradients at 20/25/28 MV/m, reduces the μ/p to ~0.059. Increasing the rotator voltage to 28 MV/m, restores μ/p to ~0.063. Increasing the density in the buncher to 34 atm with gradients at 22/28/30 MV/m one obtains ~0.58. The higher density can be accommodated with a moderate increase in rf gradients.

## BEAM COOLING IN BUNCHER/ ROTATOR

Energy loss in $H_2$ also cools the beam, with some cooling in both the buncher and rotator. This occurs in the 34 atm example and to a greater extent in the 100 atm case. The rms transverse emittance $\varepsilon_t = \sqrt{\varepsilon_+ \varepsilon_-}$ damps from ~0.018 m to ~0.0156 at 34 atm and to ~0.0128 m at 100 atm.

In the present model the beam is within a constant magnetic field. The 4D transverse emittance is the product of emittance eigenvalues, and in solenoidal fields these modes (+ and −) are associated with drift and cyclotron modes, respectively; x and y coordinates are not eigenmodes [8, 9]. The cyclotron mode coordinates then are:

$$\begin{pmatrix} \kappa_1 \\ \kappa_2 \end{pmatrix} = \sqrt{\frac{c}{eB}\begin{pmatrix} k_x \\ k_y \end{pmatrix}} = \sqrt{\frac{c}{eB}}\begin{pmatrix} p_y + \frac{eB}{2c}x \\ p_x - \frac{eB}{2c}y \end{pmatrix}, \quad (1)$$

and are simply proportional to the kinetic momentum coordinates. The drift mode coordinates are given from the following expressions:

$$\begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} = \sqrt{\frac{eB}{c}}\begin{pmatrix} d_x \\ d_y \end{pmatrix} = \sqrt{\frac{eB}{c}}\begin{pmatrix} x - \frac{c}{eB}k_y \\ y + \frac{c}{eB}k_x \end{pmatrix}, \quad (2)$$

$$\begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} = \sqrt{\frac{eB}{c}}\begin{pmatrix} \frac{x}{2} - \frac{c}{eB}p_y \\ \frac{y}{2} + \frac{c}{eB}p_x \end{pmatrix}. \quad (3)$$

and are proportional to the centers of the Larmor motion, associated with the position coordinates. Within the constant B field the cyclotron mode is damped, while the drift mode is not ($\varepsilon_+$ = 0.024 m; $\varepsilon_-$ = 0.013 m → 0.0066 m).

Field flips exchange the identity of drift and cyclotron modes, so that both modes are damped in the alternating-solenoid cooler. The initial 1-D cooling ($\varepsilon_-$ only) is useful as an initiation of cooling and reduces the required amount of downstream cooling.

## SUMMARY AND FUTURE DIRECTIONS

The present analysis indicates that a gas-filled buncher and rotator system could be used instead of the initial vacuum rf case [10]. With appropriate increases in rf gradient, μ/p similar to baseline is obtained [11]. A somewhat longer front end with a longer buncher and rotator would allow some reduction in rf voltages, and would also allow a more adiabatic capture. This would increase the number of 325 MHz bunches in the bunch train, which would be disadvantageous for a collider scenario, but not for a neutrino factory/ muon source application. This variation will be explored in the future.

With high density gas in the rotator, alternating solenoid focusing could be used to balance + and – mode cooling; this may be more efficient than the present single mode cooling in the gas-filled buncher/rotator.

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