USE OF GAS-FILLED CAVITIES IN MUON CAPTURE FOR A NEUTRINO FACTORY *

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Abstract

Recent studies indicate that gas-filled cavities can provide high-gradient acceleration and simultaneous cooling for muons. In this paper we explore using these cavities in the front-end of the capture and cooling systems for neutrino factories. We consider capturing beam in high-frequency buckets and phase-energy rotating and cooling them using gas-filled rf cavities. Scenario variants are described and studied. The same techniques could also initiate muon beam generation for a muon collider.

INTRODUCTION

For a neutrino factory, short, intense bunches of protons are focused onto a target to produce pions, which decay into muons and are then accelerated into a high-energy storage ring, where their decays provide beams of high-energy neutrinos.[1, 2, 3] The challenge is to collect and accelerate as many muons as possible. The pions (and resulting muons) are initially produced within a short bunch length and a broad energy spread, much larger than the acceptance of any accelerator.

In the neutrino factory design,[1] the π's drift from the production target, lengthening into a long bunch with a high-energy "head" and a low-energy "tail", while decaying into μ's. Then the beam is transported through a buncher that forms the beam into a string of bunches, and a "ϕ-E rotator" section that aligns the μ bunches to (nearly) equal central energies,[4] and then cooled in a ~200 MHz cooling channel with LiH absorbers. We propose using high-pressure gas-filled rf cavities[5] in the ϕ-E rotator section to combine the phase-energy rotation and cooling into a single, more compact system. (see Fig. 1) The gas can suppress breakdown, enabling higher gradient, and the gas provides energy-loss cooling. In the present paper we optimize the gas-filled system and consider variations on the concept.

BASELINE GAS-FILLED CASES

For simplicity we start with the ICOOL[7] data version of the neutrino factory front end, from which the final Study 2A version was developed.[1] (We are not initially using the final "fully-realistic" version of Study 2A in order to avoid complexity.) This version had a target within a 20T solenoid that tapers down to 2T and a drift region that is 111m long, going into a "high-frequency adiabatic buncher" that is ~51m long. The adiabatic buncher was followed by a 54m long "phase-energy rotation region", in which high-energy bunches are decelerated and low-energy bunches accelerated, while the bunch structure is maintained. This is followed by a cooling channel of ~80m length. The focusing magnetic field was constant at 2T until into the alternating solenoid field of the cooling channel. The buncher and rotator consist of 0.75m long cells with 0.5m long cavities and 0.25m long drifts. In the buncher the rf gradient gradually increases from cavity to cavity to 12 MV/m, while the rf frequency decreases from 337.5 MHz to 232 MHz along the buncher, following a rule where the reference particles (at P_μ = 280 and 154 MeV/c) remain separated by 18 rf wavelengths. In the ϕ-E rotator, the reference particle separation is set at 18.05 rf wave-lengths, so that the leading bunches are decelerated and the rear (low-energy) bunches are accelerated, all obtaining a final reference momentum of ~210MeV/c. The gradient is fixed at 12MV/m in the cavities. The rf frequency increases from 231 to 201.7 MHz and the bunches are lined up to nearly equal energies with the reference ~201.25MHz spacing.

The beam is then transversely matched from 2T to an alternating solenoid lattice for beam cooling. The Study 2A cooling channel of ~80m length consists of 0.75m long cells, with 0.5 m of 201.25 MHz rf cavities per cell with a gradient of 16 MV/m. Each of the cells has two 1cm LiH absorbers, so the baseline energy loss per ce11 is 2 × 1.59 MeV= 3.18 MeV/cell. Over an 81m length (108 cells) 343.44 MeV of energy loss occurs.

This Study 2A design obtains ~0.23 μ/p (from an initial reference production of π's from 24GeV p on a Hg target) within the reference acceptances (amplitudes ε_L<0.15, $\varepsilon_\perp$ <0.03) after ~80m of cooling, while the transverse rms emittance (normalized) is reduced from ~0.018 to ~0.008 m after the 80m cooling. With the more restricted acceptance of $\varepsilon_\perp$ < 0.015m, ~0.11μ/p is obtained.

Gas-filled Cooling ϕ-E Rotator

Following the recent proposals on gas-filled cavites for cooling and higher gradients, we used gas-filled high-gradient rf in the ϕ-E rotator, The baseline energy loss in gaseous hydrogen is dE/dx = 0.000344 P MeV/cm, where P is the pressure in atmospheres (at 295° K).[11] In the examples below we (initially) use a pressure of 150A averaged in this section, so dE/dx = 0.052 MeV/cm, or 3.9 MeV per 0.75m cell (cavity+drift). The total energy loss over 72 cells is 281MeV, equivalent to ~70m of the Study2A cooling channel. The 2T solenoid focusing is replaced by a 2.5T alternating solenoid field, with matching at the end of the buncher.

At the end of the ϕ-E rotation and cooling channel, we find ~0.22 μ/p within the Study 2A acceptances (ε_L < 0.15, $\varepsilon_\perp$ < 0.03), and with ~0.12 within (ε_L < 0.15, $\varepsilon_\perp$ < 0.015). (see fig. 2) The transverse rms emittance was cooled from ~0.019m at the end of the buncher +

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transverse match to ~0.008m at the end of the ϕ-E rotator.(see fig. 3) . This performance is approximately the same as the baseline Study 2A case. The μ acceptance can be improved by increasing the longitudinal acceptance. If the longitudinal emittance aperture were increased to 0.3m, then μ/p at $\varepsilon_\perp$ <0.03m increases to 0.26, with 0.14 at $\varepsilon_\perp < 0.015$ Figures 4 and 5 show transverse and longitudinal phase space views of ICOOL-simulated muons in this line.

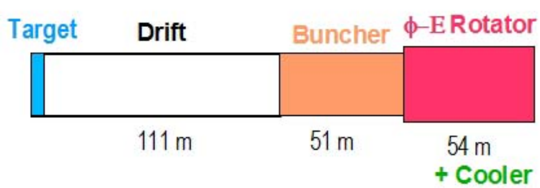

Figure 1: Layout of drift, buncher and ϕ-E rotator/cooler. The ϕ-E rotator and the cooler are combined, making the system 80m shorter than the baseline study2A system.

Lower gradient variant

The 24MV/m rf may be relatively expensive, and we consider a case with reduced rf requirements. The rf gradient was reduced to 20MV/m, while the gas density was reduced to 133 atm. At these parameters, at the end of the ϕ-E rotation and cooling channel, we find ~0.20 μ/p (ε_L<0.15, $\varepsilon_\perp$ <0.03), and with ~0.10 within the more restricted acceptances (ε_L<0.15, $\varepsilon_\perp$<0.015). The transverse rms emittance is cooled from ~0.019 at the end of the buncher to ~0.0093 at the end of the ϕ-E rotator/cooler. The performance is ~10 to 15% worse than the higher gradient example. (Some of the degradation could be recovered by extending the cooling channel.)

OTHER VARIATIONS

As a similar alternative we considered using Be or LiH slabs as the energy absorbers. These slabs could be located at the ends of the cavities, where they can close the cavity, enabling a pillbox cavity geometry. As a first example we placed 0.65 cm Be slabs at the ends of the cavities (1.3cm/ cell) The resulting energy loss is roughly equal to the energy loss in the H_2-filled cavities. However the overall performance in ICOOL simulation is somewhat less successful. The beam emittance was cooled transversely from 0.019 to 0.0115m, and the number of muons within the (ε_L < 0.15, $\varepsilon_\perp$ < 0.03) apertures is ~0.134 μ/p, and ~0.056 μ/p. The degradation in performance is somewhat greater than that expected simply from the increased multiple scattering in Be.

We also tried using LiH slabs of 1.2cm thickness; LiH has less multiple scattering than Be. After rematching, the performance was slightly improved from Be. The beam emittance was cooled transversely from 0.019 to 0.0102m, and the number of muons within the (ε_L< 0.15, $\varepsilon_\perp$ < 0.03, 0.15) apertures are ~0.15 μ/p, ~0.075 μ/p. This performance is slightly improved but is still somewhat less than expected by extrapolation from the H_2 study.

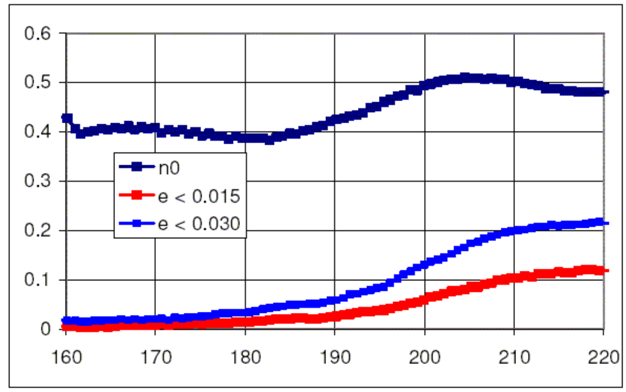

Figure 2: Capture of muons within the reference acceptances in the 24MV/m, 150atm H_2 case. The horizontal axis is distance along the transport in m. (The ϕ-E rotator cooler begins at z=163 and ends at z=217m.) The upper trace is total μ/p; the lower traces are μ/p in the acceptance of $\varepsilon_L < 0.15$, $\varepsilon_\perp < 0.03$ and $\varepsilon_\perp < 0.015$.

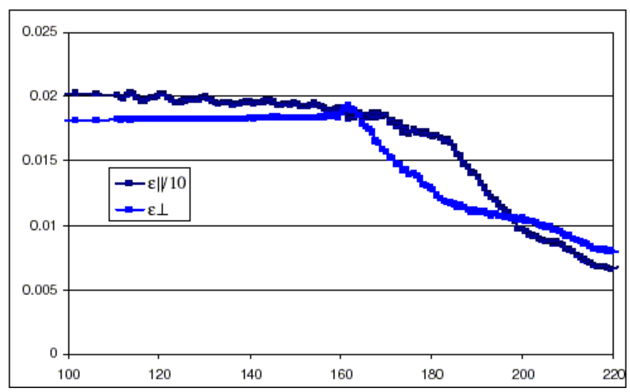

Fig. 3 Reduction of transverse emittance $\varepsilon_\perp$ in the capture channel; the ϕ-E rotator/cooler begins at z=163 and ends at z =217m; $\varepsilon_\perp$is reduced from ~ 0.019 to 0.008m. ($\varepsilon_\|$ tracks the capture into 200MHz buckets.)

COMMENTS ON COSTS

A critical parameter is the impact of the new system on the cost of the ν-Factory facility (savings or increase). We use the methodology of Palmer and Zisman to obtain an estimate. In ref. [8] they estimated the cost of Study 2A, scaling according to the expected cost variations on length, gradient, aperture sizes and field strengths. We eliminate the Study 2A cooling system, which has a total cost of 185M$, and add cooling capability to the phase rotation section, which remains about the same length, with similar total cavity length (56.25m goes to 54m). The major change is in the increased rf gradient (12.5 MV/m is increased to 20 or 24 MV/m). The total rf voltage increases from ~470MV to ~720 or ~864MV. The cavity costs remain about the same (12M$), but the power supply cost increases as the square of the gradient.

The Rotator power supply costs then increase from 44M$ (Study 2A) to 107M$ (20MV/m) or 155M$ (24MV/m).

The magnet system in the rotator is a 2.5T alternating solenoid rather than a 1.75T constant field. The magnet costs increase from 23 to 26.2 M$. We assumed a cost increase of ~10M$ from structures and diagnostics due to the change from a vacuum system to a gas-filled system (133 to 150 atm at 20°C). Summing over the various effects, we find that the total ν-factory cost decreases by ~110M$ with 20 MV/m rf, and by ~62M$ with 24MV/m.

CONCLUSIONS AND DISCUSSION

These initial examples demonstrate that H_2 gas-filled rf cavities can be inserted into the phase-energy rotation section and provide cooling at least as good as that provided in the optimized Study 2A scenario. Use of solid Be or LiH absorbers is also possible, but our initial study showed somewhat reduced performance (25 to 30% worse). Future studies will determine whether that reduction is intrinsic, and whether the gas-filled rf cavity approach is dramatically better.

The extrapolations from Study 2 cost estimates indicate that the present approach could be significantly more affordable than Study 2A, mainly because combining the rf rotation and cooling functions reduces the system length by ~80m, and the more compact system has reduced costs.

The rf cavity studies [5,6] indicate that H_2-gas-filled cavities may obtain higher gradient than vacuum-filled cavities, particularly with the magnetic fields needed for focusing. (Vacuum cavities may not even reach the required gradients.) The present examples establish that a high-performance ν-factory front end can be developed using the gas-filled cavities for simultaneous high-gradient rf and energy-loss cooling.

This study demonstrates a possible configuration for a ν-factory front end, but does not establish a fully optimized design. Future studies will consider many other variations (shorter or longer systems, obtaining shorter or longer bunch trains, matching into different rf systems and apertures, use of more cooling, etc.) The possibilities enabled by high-gradient H_2-gas-filled rf will greatly enhance these explorations. Variations on the technique will also be explored in preparing muon beams for a μ^+-μ^- collider.

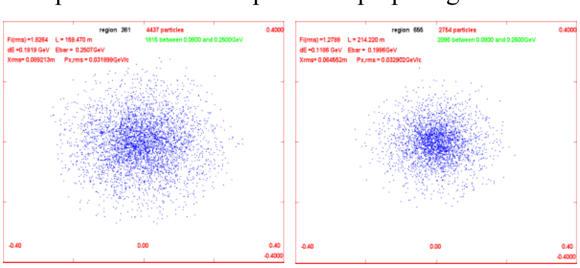

Fig. 5. Transverse beam profiles (x-y) before and after the capture transport, showing the effect of the gas-cavity cooling on beam size. (Vertical and horizontal axes are ±0.4m)

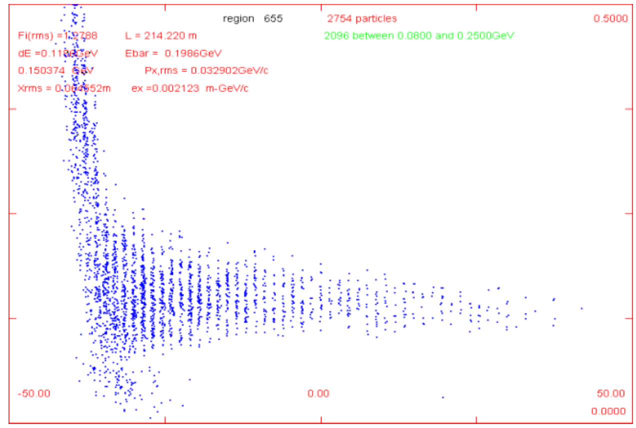

Fig. 4. Longitudinal phase space of μ's at the end of the buncher/rotator. The μ's are formed into a ~60m long string of 200 MHz bunches. The bunch train is shorter and denser than the Study 2A example. (Horizontal axes are ±50m, Vertical axis is 0 to 0.5 GeV kinetic energy.)

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