MUON CAPTURE, PHASE ROTATION, AND PRECOOLING IN PRESSURIZED RF CAVITIES*

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Abstract
Gas-filled RF cavities can provide high-gradient accelerating fields for muons, and can be used for simultaneous acceleration and cooling of muons. In this paper we explore using these cavities in the front-end of the capture and cooling systems for neutrino factories and muon colliders. We consider using gas-filled RF cavities for the initial front end cooling systems. We also consider using them for simultaneous phase-energy rotation and cooling in a front-end system. We also consider using lower-density RF cavities, where the gas density is primarily for RF breakdown suppression, with less cooling effect. Pressurized RF cavities enable higher gradient RF within magnetic fields than is possible with evacuated cavities, enabling more options in the front-end. The status of designs of the capture, phase rotation, and precooling systems of muon beams in pressurized cavities is described.

INTRODUCTION

Bright Muon beams are required for muon colliders, neutrino factories and intense muon sources. For a neutrino factory (or muon collider), short, intense bunches of protons are focused onto a target to produce pions, which decay into muons, that are collected and cooled, 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.

In the neutrino factory design study 2A,[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 bunched into a string of bunches in a "Buncher", followed by "ϕ-E rotator" section that aligns the μ bunches to (nearly) equal central energies (matched into 200 MHz spacing), and then cooled in a ~200 MHz cooling channel with LiH absorbers.[4] (see fig. 1)

The buncher requires ~300 MHz rf cavities at ~5MV/m, while the rotator requires ~220MHz rf at ~10MV/m, both within a ~2T solenoid. The cooler requires ~15MV/m 200 MHz rf within alternating-solenoid focussing. It is not certain that rf can be operated reliably at these parameters within vacuum cavities. Experiments have shown that high-pressure H_2-gas filled rf cavities can operate at up to 50 MV/m, with no gradient loss in high magnetic fields.[5, 6] In this note we exploit this apparent capability in designing variations on this front end concept. The energy loss of muons in H_2-gas also provides an ionization cooling effect that can be beneficial in front end design.

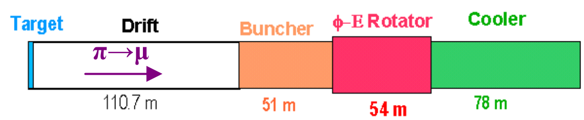

Figure 1: Layout of the Study 2A neutrino factory front end, showing an initial drift from the π production target, a buncher with low-gradient rf. a "ϕ-E rotator" section with higher gradient rf, and a cooler transport with rf and LiH absorbers.

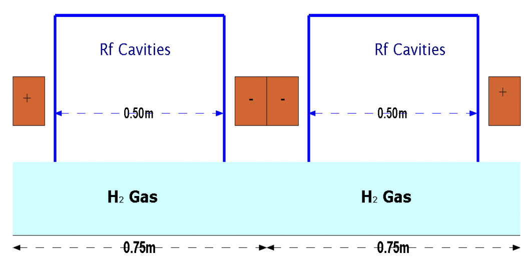

Figure 2: A cell of the gas-filled cooling system. (radial cross-section view) This contains 0.5m long "pillbox" 201.25 MHz rf cavities, with 0.25m gaps between cavities containing coils for magnetic fields. The H_2 gas fills the center of the transport with a uniform density.

GAS-FILLED COOLER LATTICE

As a first application we consider replacing the LiH absorbers with H_2 gas. In a simplest configuration the gas fills the entire transport of the cooling section (rf cavities and drift spaces between cavities (see fig. 2)). The gas density is chosen to provide the same energy loss per 0.75m half-cell as 2cm LiH. This corresponds to ~125Atm equivalent density. The rf gradient is 15MV/m in the rf cavities. The equilibrium emittance with H_2 is ~60% of that with LiH, so we do expect some what improved cooling. Simulations with both ICOOL and G4 beamline showed significant improvement.[7, 8]

Fig. 3 shows results of the simulation of a ν Factory Front End in G4Beamline. In that example the front end consisted of a Hg target within a 20T→2T solenoid, an initial Drift of 57m. a 31m Buncher and a 36m long Rotator leading into a 90m long cooler. The cooler

*Work supported by US DOE under contract DE-AC02-07CH11359 and SBIR grant DE-FG02-05ER86252 and FRA DOE contract number DE-AC02-07CH11359
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consisted of alternating solenoid cells with either H_2 gas absorber throughout, as displayed in fig. 2, or vacuum filled with LiH slabs, as used in Study 2A. Fig. 3 shows the number of muons within the ν-Factory acceptance along the Cooler with either LiH absorbers or 2 different densities of H_2-gas-filled cooling. As the beam is cooled, more μ's are within the ν-factory acceptance. After ~80m of LiH cooling, ~0.06 μ/p (8GeV) are accepted, while with H_2 cooling ~0.08 μ/p is obtained, with no sensitivity to small density changes.

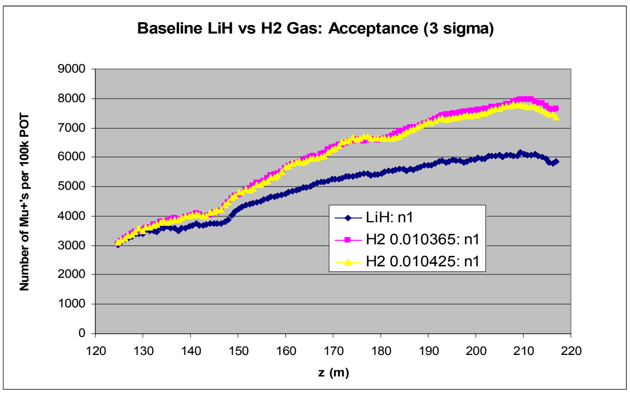

Figure 3. A comparison of muon capture with gas H_2 cooling or LiH cooling, as simulated using G4Beamline. The gas H_2 example obtains 33% more μ/p than the case with LiH cooling. H_2 density is 0.0104 gm/cm^3.

GAS-FILLED ROTATOR AND COOLER

As a further configuration, we propose using high-pressure gas-filled rf cavities[5] in the ϕ-E rotator section to combine 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.

We began with the ICOOL[7] version of the neutrino factory front end, from which the Study 2A version was developed, which is displayed in fig. 1.[1] This version has 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", followed by a cooling channel of ~80m length. The focusing magnetic field is constant at 2T until into the alternating solenoid field of the cooling channel. This design obtains ~0.23 μ/24 GeV p 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.

In the present variant, we use 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] We (initially) use a pressure of 150Atm averaged in this section, so dE/dx = 0.052MeV/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 2.8T 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(24 GeV) within the Study 2A acceptances (ε_L < 0.15, $\varepsilon_\perp$ < 0.03), with ~0.12 within the smaller acceptance(ε_L<0.15, $\varepsilon_\perp$<0.015). (see fig. 4) The transverse rms emittance was cooled from ~0.019m at the end of the buncher + transverse match to ~0.008m at the end of the ϕ-E rotator. 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 $\varepsilon_\perp$ < 0.015m.

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 ~0.019m at the end of the buncher to ~0.0093m at the end of the ϕ-E rotator/cooler. The performance was ~10 to 15% worse than the higher gradient example. The reduced performance is largely due to the reduced cooling. Adding ~30m of additional cooling cells at the study 2A parameters increases the acceptance to ~0.23μ/p (0.126 at $\varepsilon_\perp$<0.015) while cooling transverse emittances to ~0.0079m.

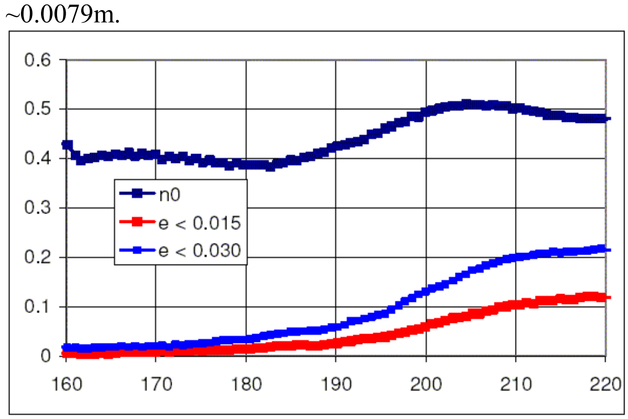

Figure 4: Capture of muons within the reference acceptances in the 24MV/m, 150atm H_2 case. The horizontal axis is distance along the transport in m. (The ϕ-E rotator cooler begins at z=163 and ends at z=217m.) The upper trace is total μ/p; the lower traces are μ/p in the acceptance of ε_L < 0.15m, $\varepsilon_\perp$ < 0.03m and $\varepsilon_\perp$ < 0.015m.

We also considered using Be or LiH slabs as the energy absorbers. These slabs were located at the ends of the cavities, where they can close the cavity, enabling a pillbox cavity geometry. However the overall performance in ICOOL simulation was somewhat less successful. The number of muons within the ($\varepsilon_L < 0.15$m, $\varepsilon_\perp < 0.03$m) apertures is ~0.134 μ/p for Be and 0.15 for LiH. The degradation in performance is somewhat more than that expected simply from the increased multiple scattering.

LOW-DENSITY GAS-FILLED φ-E ROTATOR

In this variant the rotator is filled with a low density of H_2 gas. The role of the gas here is simply to prevent breakdown, and experiments indicate that only ~15-atm equivalent density is needed to prevent rf breakdown; this is ~10% of that used in the combined buncher-cooler discussed above or in the gas-filled cooling channel. The gas itself would therefore provide only a small amount of energy loss and the basic beam dynamics would only be a small perturbation on the baseline described above. To confirm this discussion we simulated the front end under those assumptions.

In an initial example we chose a front end based on fig. 1, but with an initial buncher limited to 6 MV/m gradient, and a rotator with gas-filled cavities at 15atm density (within the alternating solenoid lattice shown in fig. 2), and a cooler with LiH absorbers. (The limited buncher gradient and alternating solenoid lattice were chosen as variants that may be more likely to avoid breakdown.). The ICOOL simulation showed reasonably good acceptance, essentially the same as similar simulations without gas-filled rf. ~0.2μ/p(24GeV) are obtained after ~75m of LiH cooling within ($\varepsilon_L<0.15$, $\varepsilon_\perp<0.03$). The beam is cooled from ~0.018m to 0.016 within the H_2 and then from 0.016 to 0.0075m with the LiH absorbers.

In another variation, the rotator was placed in a constant B=2T field, with (or without) 15atm H_2 density, and with a 125atm H_2 cooling section. These examples placed the configuration in an idealized study2A baseline, and the performance was significantly better. This example obtains ~0.31μ/p(24GeV) without gas in the rotator and ~0.29μ/p(24GeV) with gas in the rotator to suppress breakdown. The results also indicate the level of improved performance possible with gas-filled rf throughout. (With LiH cooling rather than H_2 cooling, ~0.26μ/p(24GeV) are obtained.)

CONCLUSIONS AND DISCUSSION

These initial examples demonstrate that H_2 gas-filled rf cavities can be inserted into the phase-energy rotation section and cooling sections and obtain muon capture and cooling as good or better than that in the optimized Study 2A scenario. 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. Variations on the technique can also be explored in preparing muon beams for a μ^+-μ^- collider.

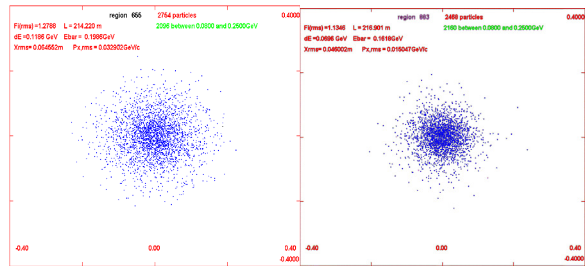

Figure 5. Transverse beam sizes in the front end after equivalent energy-loss LiH cooling(left) and after gaseous H_2 cooling(right). (Horizontal and vertical axes are ±0.4m)

REFERENCES

[1] "Cost-effective Design for a Neutrino Factory", with J. S. Berg, S. A. Bogasz, S. Caspi, J. Cobb, R. C. Fernow, J. C. Gallardo, S. Kahn, H. Kirk, R. Palmer, K. Paul, H. Witte, M. Zisman, **Phys. Rev. STAB 9**,011001(2006)

[2] N. Holtkamp and D. Finley, eds., A Feasibility Study of a Neutrino Source based on a Muon Storage Ring, Fermilab-Pub-00/108-E (2000).

[3] S. Ozaki, R. Palmer, M. S. Zisman, eds., BNL-52623, June 2001. http://www.cap.bnl.gov/mumu/studyII/FS2-report.html.

[4] D. Neuffer, "'High Frequency' Buncher and Phase Rotation", Proc. NuFACT03, **AIP Conf. Proc. 721**, p. 407. (2004).

[5] R. Johnson et al., "Recent Innovations in Muon Beam Cooling and Prospects for Muon Colliders", invited paper, Proc. PAC2005, Knoxville, TN (2005).

[6] R. E. Hartline et al., Fermilab MUCOOL-Note-285, 2005.

[7] R. Fernow, "ICOOL Simulation Program" Proc. 1999 PAC, New York, p. 3020 (1999), http://pubweb.bnl.gov/people/fernow/ICOOL

[8] T. Roberts, G4beamline, http://g4beamline.muonsinc.com