MuCool Note 335

More Studies on Cooling within High-Frequency Phase Rotation

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Abstract. The scenario for capture, bunching, and phase-energy rotation with cooling of μ's from a proton source is explored. In the previous study[1], we used a high-density gas transport within the phase-energy rotator to obtain cooling. In the present note we consider further optimization of that scenario and consider replacing the high density gas with solid absorbers. Initial results obtain somewhat diminished performance with solid absorbers. Cost implications of these scenarios are also discussed.

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.[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 baseline neutrino factory design, [4, 5, 6] this beam is transformed into a longer string of bunches with a relatively small energy spread.

In the neutrino factory design study 2A,[4, 5, 6] 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 an "rf rotator" section that aligns the μ bunches to (nearly) equal central energies, and then cooled in a ~200 MHz cooling channel with LiH absorbers. In MuCOOL-324 we proposed using high-pressure gas-filled rf cavities in the rf rotator section to combine the phase-energy rotation and cooling into a single, more compact system. (see Fig. 1) The gas can suppress breakdown, possibly 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 Cavity Case

For simplicity we started with the initial ICOOL[9] version presented by Palmer in December 2003, from which the final Study 2A version was developed.[5] This case 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.

This Study 2A initial example obtains ~0.23 μ/p within the study 2a reference acceptances ($\varepsilon_L < 0.15$, $\varepsilon_\perp < 0.03$) 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. With no cooling (beam at exit of the ϕ-E rotator), the acceptance is 0.103 and 0.049 μ/p within the 0.03 and 0.015 acceptances, respectively.

In our initial gas-filled case,[1] the target, drift and buncher remained the same as in the Study 2A baseline. The beam transport (cavities and drifts) were filled with a density of gas corresponding to 133A (at 295ºK), so dE/dx = 0.0458 MeV/cm, or 3.43 MeV per 0.75m cell (cavity + drift). The total energy loss over 72 cells is 247MeV, equivalent to ~60m of the Study2A cooling channel. The baseline gradient in the rf was 20MV/m, increased from the Study 2A value of 12.5MV/m to compensate for the energy loss.

At the end of the ϕ-E rotation and cooling channel, we find ~0.196 μ/p within the Study 2A acceptances ($\varepsilon_L < 0.15$, $\varepsilon_\perp < 0.03$), and with ~0.101 within the more restricted acceptances ($\varepsilon_L < 0.15$, $\varepsilon_\perp < 0.015$). The transverse rms emittance had been cooled from ~0.0192m at the end of the buncher + transverse match to ~0.0093m at the end of the ϕ-E rotator

Reoptimized Gas-cavity Phase-Rotator-Cooler Example

In a further optimization the gas pressure was increased to 150atm, and the rf voltage was increased to 24MV/m. With these parameters, the transverse cooling was increased while the muon capture was slightly improved.

At the end of the ϕ-E rotation and cooling channel, we find ~0.216 μ/p within the Study 2A acceptances ($\varepsilon_L < 0.15$, $\varepsilon_\perp < 0.03$), and with ~0.12 within the more restricted acceptances ($\varepsilon_L <$ 0.15, $\varepsilon_\perp < 0.015$). The transverse rms emittance was cooled from ~0.0192m at the end of the buncher + transverse match to ~0.0081m at the end of the ϕ-E rotator.

The rms longitudinal emittance of the beam at this point is ~0.07. The μ acceptance could be improved by increasing the longitudinal emittance acceptance. If the longitudinal emittance aperture were increased to 0.3m, then μ/p at $\varepsilon_\perp$ <0.03m increases to 0.257, with 0.140 at $\varepsilon_\perp <$ 0.015.

Other Variations: Be and LiH Cooling

At an initial presentation, it was suggested that similar cooling with bunching could be obtained by Be or LiH slabs, perhaps located at the ends of the cavities, where they can close the cavity, enabling an actual pillbox geometry. The slabs are designed to provide the same energy loss as the gas-filled cells and the rf cavities have the enhanced gradient. Similar performance should be obtained, but Be and LiH have greater multiple scattering, and would not cool quite as effectively.

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 equivalent to the energy loss in the H_2-filled cavities. However the overall performance in ICOOL simulation was somewhat less successful than the H_2-gas cavity cooling. The beam emittance was cooled transversely from 0.019 to 0.0115m, and the number of muons within the ($\varepsilon_L < 0.15$, $\varepsilon_\perp < 0.03$) 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 expect that the matching of optics and phases has deteriorated.

We also tried using LiH slabs of 1.2cm thickness; LiH has less multiple scattering than Be. After some 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 ($\varepsilon_L <$ 0.15, $\varepsilon_\perp < 0.03$) apertures is ~0.150 μ/p, and ~0.075 μ/p. This performance is slightly improved but is still somewhat less than expected by extrapolation from the H_2 study.

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 a first estimate. In ref. [11] they estimated the cost of Study 2B based on the Study 2 cost estimates, scaling the various changes in the system according to the expected cost variations on length, gradient, aperture sizes and field strengths.

In the present scenario we eliminate the separate cooling system, which has a total cost of 185M$, and add cooling capability to the phase rotation section, which remains about the same length, with similar total cavity length (56.25m goes to 54m). The major change is in the increased rf gradient (12.5 MV/m is increased to 20 or 24 MV/m). The total rf voltage increases from ~470 MV to ~720 or ~864MV. The cavity costs remain about the same (12M$), but the power supply cost increases as the square of the gradient. The Rotator power supply costs then increase from 44M$ to 107M$ (20MV/m) or 155M$ (24MV/m).

The magnet system in the rotator is a 2.5T alternating solenoid (0.486 M$/m) rather than a 1.75T constant field (0.409 M$/m). The magnet costs increase from 23 to 26.2 M$.

The cost and scaling of diagnostics is unclear; ref. [11] has 11.5 k$/m for the drift, 83k$/m for the buncher, 11.5k$/m for the rotator, and 259k$/m for the cooler. Diagnostics for the rotator really should be at least as much as the buncher (both have rf systems, and must track bunch behavior). We assume the added cost of the cooler is due to the presence of the absorbers and we therefore conservatively assume the new rotator (with cooling) requires similar costs. The total for diagnostics would be 14 M$, increased from 0.65 M$ (at 11.5k$/m) or 5M$ (at 89k$/m).

The other change is from a vacuum transport and cavity to a gas-filled system (133 to 150 atmospheres at room temperature). We have not yet estimated a cost difference for this, unless it is included in the above diagnostics with absorbers costs.

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 a similar level to that provided in the 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 can be significantly better.

Extrapolations from the Study 2B results indicate that the present approach could be significantly more affordable than Study 2B, simply because combining the rf rotation and cooling functions reduces the system length by ~80m, and the more compact system has reduced cost, even though rf power costs may be increased.

Many other variations on the neutrino factory front end can be considered and studied; it is unlikely that we have yet developed a fully optimized system.

Acknowledgments

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Figure 1: Layout of the modified μ capture and cooling section. Protons on target produce π's that decay to μ's and drift to a total of 111m. The muons are bunched within the 51m long buncher and the bunches are rotated to nearly equal energies within the rf rotator while being cooled transversely by absorbers within the rf rotator. In the Study 2A version the rotator was followed by a 80m long cooling section.

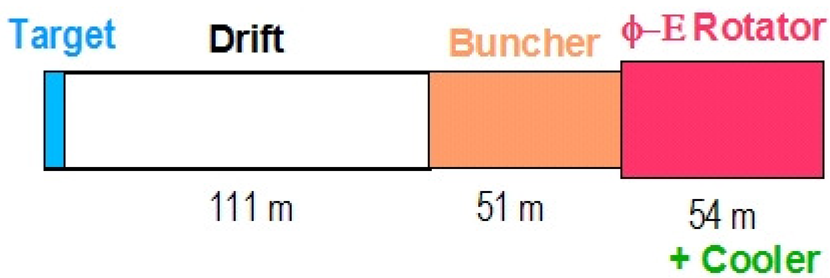


Figure 2: Layout of a cell in the Rotator/Cooler. The projection begins at the center of an rf cavity, shows a magnetic coil, a full rf cavity space, and a second coil with opposite current. The lower graph shows the alternating solenoid field strength, which fluctuates from +2.5T to -2.5T in the 1.5m cell.

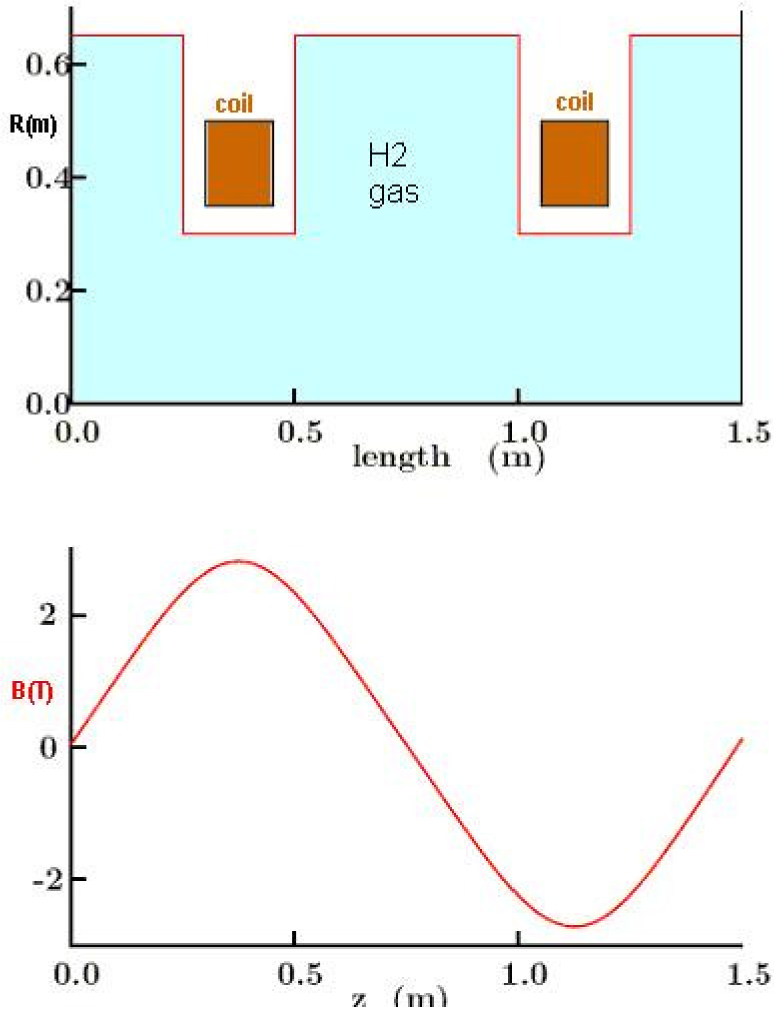


Figure 3A: All muons and muons accepted within the design transverse amplitudes of 0.015 and 0.03m and the design rf buckets for the gas-filled cavity case.

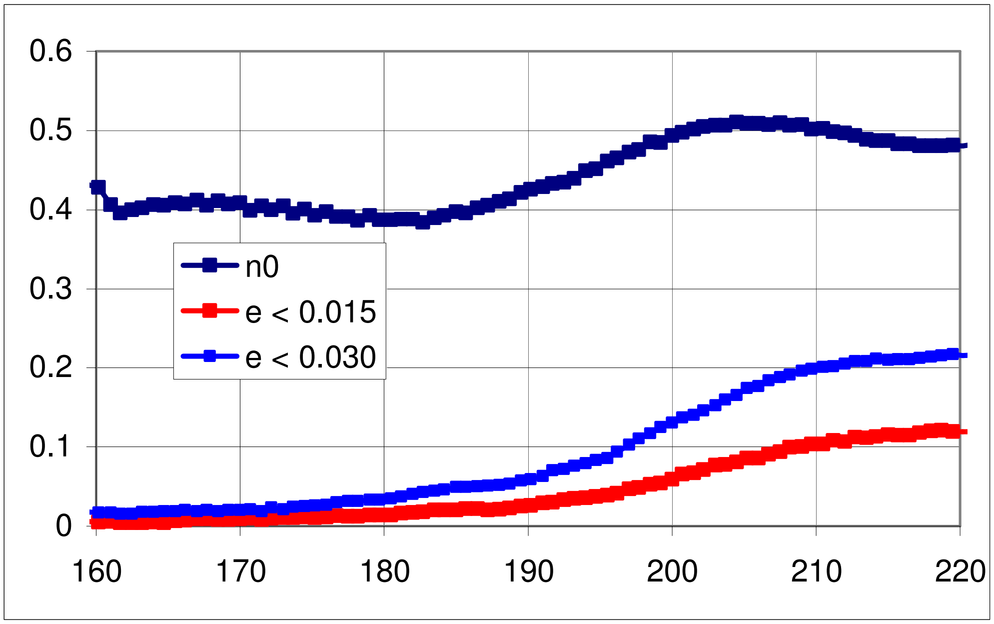


Figure 3B: Transverse emittance cooling with gas-filled phase rotation cavities: The transverse emittance is cooled from ~0.019m to ~0.081m over the ~54m ϕ-E rotation and cooling channel following the buncher: the separate cooling channel is not required.

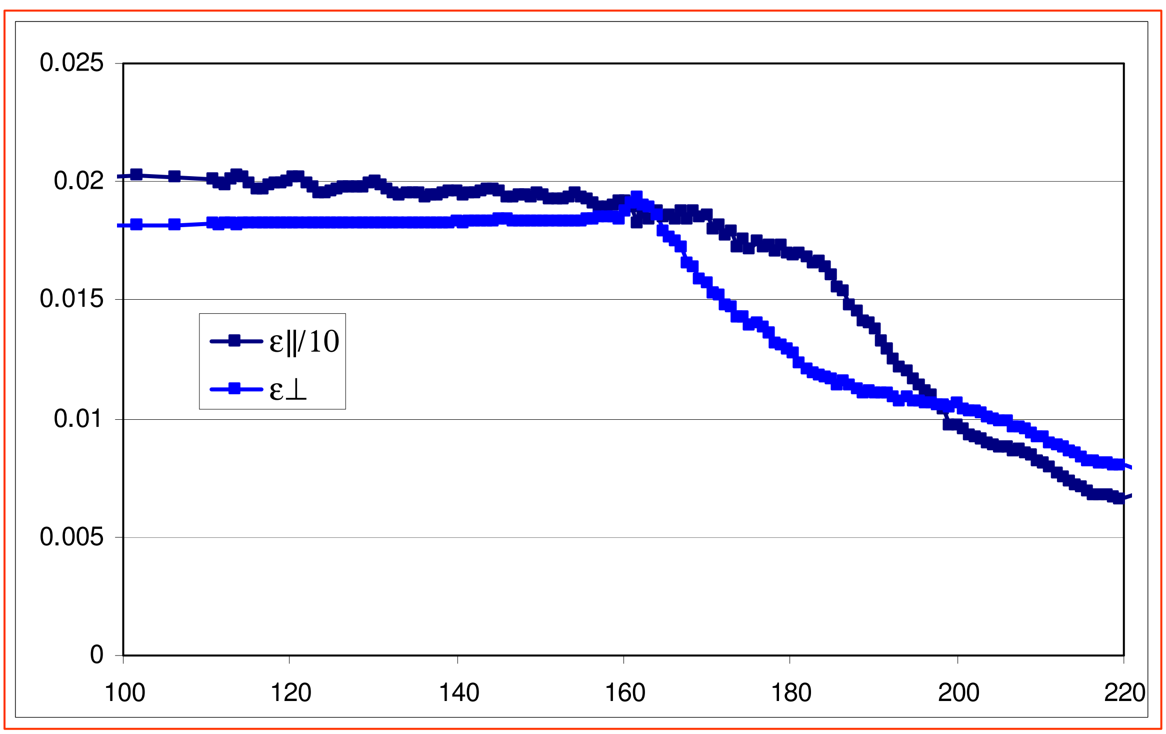
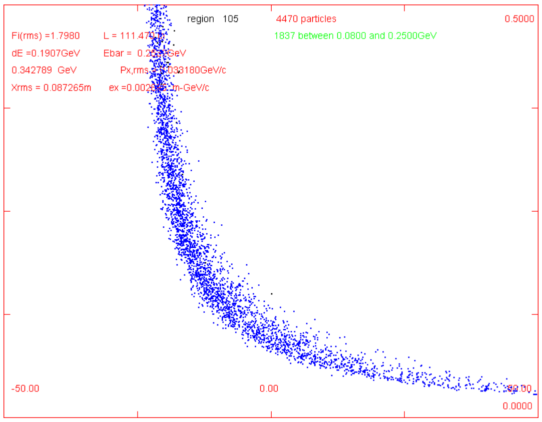
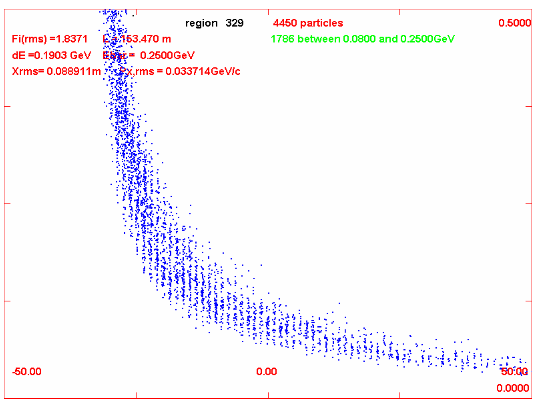


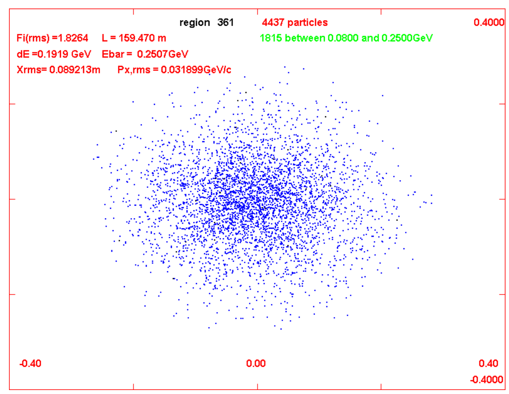
Figure 4: ICOOL simulation results of the buncher and phase rotation with gas-cavity cooling, at the parameters of the example described in the text. Figure A: μ's at z=110m; end of drift section B: μ's at z=162m, the end of the buncher. The beam has been formed into a string of ~200MHz bunches at different energies. BT: Transverse (x-y) profile of the beam at the end of the Buncher, before transverse cooling. C: At z= 215m after ϕ-δE rotation with gas-cavity cooling; the bunches are aligned into nearly equal energies. CT: Transverse profile (x-y) af the beam after cooling In plots A, B, C the vertical axis is kinetic energy (0 to 0.5 GeV) and the horizontal axis is longitudinal position (-50 to 50m) with respect to a center particle. In Plots BT and CT the coordinates are x and y (0.4 to 0.4m).



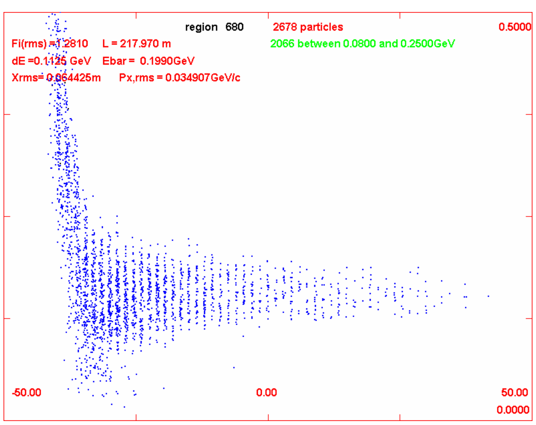
A: L=111m, (after drift)



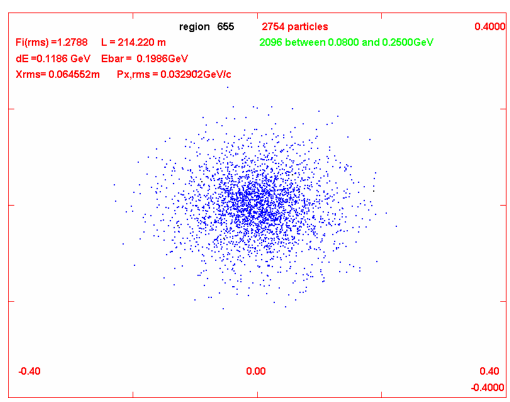
B: L=163m (after buncher)



BT: x-y beam before cooling



C: L= 217m (after ϕ-E Rotation and cooling)



CT: x-y beam after cooling and rotation.

Figure 5. Rotation/cooling cell with Be windows (approximately equivalent to the gaseous H_2 energy loss) .