MuCOOL-269

Exploration of the "High-Frequency" Buncher Concept

D. Neuffer
Fermilab

Abstract

A new scenario for capture, bunching and phase-energy rotation of μ's from a proton source is explored. In an initial example, it consists of a drift section, a changing frequency ~300→~200 MHz bunching section, followed by a fixed or changing frequency (~200 MHz) ϕ-δE rotation section. The system is a preferred alternative to the induction linac + buncher scenarios developed for the neutrino factory feasibility studies. The total rf required for this system is relatively modest, it uses established technology, and it should be substantially less expensive than previous induction linac or low-frequency systems. It would also simultaneously capture both positive and negative muons in similar bunch trains. Optimization and variations are discussed; the concept can work for a wide range of rf frequencies and bunch train lengths.

1. Introductio

The muon collaboration is exploring possible applications of muon beams in future high-energy colliders and neutrino sources.[1, 2, 3, 4] In these scenarios muon bunches are cooled, accelerated and then stored in multi-GeV storage rings. The muons are created from short, intense proton bunches incident on a high-density target, producing pions which are captured in a focusing transport and decay, that then form short muon bunches with a broad initial energy spread.

Following the transport capture, the muon beams must be matched into the following cooling and/or acceleration systems. The initial step is to reduce the energy spread. In the collider studies [1, 2] this is done by phase-energy rotation using low-frequency rf (~30 MHz), which is matched into a low-frequency initial cooling system. For the ν-factory scenarios, [1, 3, 4] an induction linac is used to to decelerate the high-energy "head" and accelerate the low-energy "tail" of a muon bunch, obtaining a long bunch (~30-100m) with small energy spread (~10 MeV). This is trapped into a train of 200 MHz bunches, which is then injected into a 200 MHz cooling system. (~200 MHz rf systems may be an optimum in cost/acceptance for cooling.) Both of these methods require development and construction of large and expensive novel acceleration systems, with gradients and total voltages substantially larger than currently available.

More recently, a variant capture and phase/energy rotation system using only ~200MHz rf has been developed.[5, 6] In this variant, the muons first drift, lengthening into a long bunch with a high-energy "head" and a low-energy "tail". Then, the beam is transported though an "adiabatic buncher", a section of rf cavities that gradually increase in gradient and decrease in frequency (from ~300 to ~200MHz). The rf wavelength is fixed by requiring that reference particles at fixed energies remain separated by an integer number of wavelengths. This forms the beam into a string of bunches of differing energies (see fig. 4). Following the buncher, the beam is transported through a high-gradient "rf rotator" section that performs a phase-energy rotation that aligns the bunches to (nearly) equal central energies, suitable for injection into a fixed-frequency ~200 MHz cooling system. (The method has the significant advantage of obtaining trains of both positive and negative muons from the same system.)

This high-frequency bunching and phase-energy rotation uses present technology and should be much more affordable than low frequency options. Much more simulation and optimization study is needed to determine whether it traps sufficient useable muons for cooling and acceleration. Fully realistic simulations of the 6-D phase space dynamics for a neutrino factory must be completed and reoptimized. However, from the present analysis we believe the approach will have effective performance, and should be established as the baseline initial section of neutrino factory design.

2. Example: Capture into 200 MHz for a Neutrino Factory

To illustrate the method and its components, we discuss its application to a reference problem of forming a muon bunch with large energy spread into a long string of bunches matched into ~200MHz rf, and present 1-D simulations of the process, tracking the longitudinal phase–energy motion.

2.1 Drift +Adiabatic Buncher

We set an initial reference kinetic energy T_0 = 125MeV. With $m_\mu c^2$ =105.66 MeV, we find

$$\frac{1}{\beta_0} = \frac{T_0 + m_\mu c^2}{\sqrt{(T_0 + m_\mu c^2)^2 - (m_\mu c^2)^2}} = 1.12497 ,$$

where $\beta = v/c$. The reference momentum $P_0 = ((T_0 + m_\mu c^2)^2 - (m_\mu c^2)^2)^{1/2} /c$ = 205.37 MeV/c. The rf frequency and phase would be set so that the reference particle passes through at zero phase.

To set a bunch timing spacing to ~200MHz (λ_{rf} = 1.5m) at the end of the drift + buncher, we require

$$L_{tot}\left(\frac{1}{\beta_1} - \frac{1}{\beta_0}\right) = L_{tot}\,\delta\left(\tfrac{1}{\beta}\right) = \lambda_{rf} = 1.5\text{m}$$

Here L_{tot} is the total distance from the target (the muon source) to the end of the drift + buncher section. If we set L_{tot} = 150m, we then require that the reference difference of inverse β's, $\delta(1/\beta)$, is given by $\delta(1/\beta) = 0.01$. If the 200 MHz rf cavity at z = 150m is set to have zero phase when the reference particle passes through it, then other test particles which differ in the parameter $(1/\beta)$ by integer multiples of 0.01 will pass at zero phase (integer × 360° away). The complete buncher contains a string of rf cavities starting from an initial position $z = z_0$, continuing up to $z = L_{tot}$. The reference particles of the bunches would all remain at zero phase if the wavelength of each cavity is given by:

$$\lambda_{rf}(z) = \delta\left(\tfrac{1}{\beta}\right) z ,$$

and the reference particle remains at zero phase.

For the initial reference example, we start with a drift with a length of z_0 = 90m, during which the muons develop a position-energy correlation (see fig. 2A), and follow it with a 60m long rf buncher. At $\delta(1/\beta) = 0.01$, we find that the frequency of the rf begins at 333MHz (λ_{rf} = 0.9m) and reduces to 200 MHz along the buncher. If the rf gradient increases gradually along the buncher, the beam can be adiabatically captured into a string of bunches, each of them centered about test particle positions with energies determined by the $\delta(1/\beta)$ spacing:

$$\frac{1}{\beta_n} = \frac{1}{\beta_0} + n\,\delta\left(\tfrac{1}{\beta}\right) \text{, which implies:}$$

$$T_n = m_\mu c^2 \frac{\frac{1}{\beta_0} + n\delta\left(\frac{1}{\beta}\right)}{\sqrt{\left[\frac{1}{\beta_0} + n\delta\left(\frac{1}{\beta}\right)\right]^2 - 1}} - m_\mu c^2 .$$

For the reference example, we choose a quadratic increase in gradient:

$$E_{rf}(z) = 4.8 \frac{(z - z_0)^2}{(L_{tot} - z_0)^2} \quad \text{MV/m} .$$

(In future reoptimizations, linear increases in gradient, and other dependences, as well as changes in final gradient magnitude can be considered.)

Fig. 2B shows 1-D simulation results of beam at the end of this buncher. The beam is formed into a train of different energy bunches.

2.2 "Vernier" Rf Rotator

The rf in the section following the buncher is used to form the string of different-energy bunches into a string with (approximately) the same central energies. In this section we describe the vernier rotation mechanism and illustrate the process in the reference example.

In initial implementations of the high-frequency capture concept, the rf frequency was fixed at the end of the adiabatic buncher, and high-gradient rf was applied to obtain a rotation of the central energies of the bunches, obtaining approximately constant central energies of bunches near the reference bunch after ~1/4 synchrotron oscillations. In 3-D simulations (6-D phase space), Van Ginneken noted that capture was somewhat improved if the rf frequency is tuned to remain slightly greater (~1%) than the bunch spacing frequency, and if that ratio is maintained until the bunches are roughly aligned in energy.[7] In this paper, we simplify and quantify this "vernier rotation" procedure within 1-D simulations and present it as the preferred scenario for high-frequency rotation.

In this initial reference example, we keep the buncher reference particle (T_0= 125MeV) and choose as a second reference particle the buncher test particle at n = 10. This particle has $1/\beta_{10}$ = $1/\beta_0$ + 10 $\delta(1/\beta)$ = 1.22497, or T_{10} = 77.281 MeV. This test particle initially trails the first reference particle by $\Delta ct = 10\lambda_{rf}$ = 15m. For vernier bunching, the first reference particle remains at zero phase, but the rf wavelength is changed to place the second particle at an acceleration phase. For the initial reference example, this is done by setting $\lambda_{rf} = \Delta ct/10.1$, which then places the second reference particle (which is the center of bunch 10) at ϕ_{10} =36° phase. $\delta\lambda/N\lambda_{rf}$, defined as the vernier offset parameter is 0.1/10 for this case. Through the length of the vernier rotator, the rf wavelength is changed to maintain this phase, which means the reference particle energy changes following:

$$T_{10}(z_R) = T_{10}(0) + e\,E_{rf} \sin(\phi_{10})\, z_R \ ,$$

where z_R indicates distance within the rotator. Other test particles corresponding to other bunches would show proportional changes ($\phi_n \cong \phi_{10}$ n/10). For the reference case, we choose E_{rf} = 10 MV/m, and choose a rf rotator insert length of $z_{R,final}$ = 7.84m , at which distance $T_{10} \cong T_0$, and the bunches are aligned with nearly equal energies. Simulation results showing beam at the end of the rotator (beginning of cooler) are shown in fig. 2C. Over the length of the rotator, λ_{rf} increases from 1.485 to 1.517m.

At the end of the rotator, the muon bunches are aligned in energy, and can be matched into a constant-frequency cooler. The rf frequency of the cooler should be rematched to place all bunches at the same phase, which means that the rf phase spacing between the reference particles should become integer ($\Delta ct = 10\lambda_{rf}$). In the reference example, this means increasing λ_{rf} to 1.532m.

The vernier rotation produces more uniform bunch energies than the fixed-frequency rotation. Since the applied rf voltages are sinusoidal rather than linear, and the initial bunch position-energy distribution is also not fully linear, we do not expect completely uniform bunch energies after rotation. However these nonlinearities are of opposing signs and cancel somewhat in the rotation. (Rotation parameters could be fine-tuned to improve the cancellations.) Also, while a high-gradient rotation is desirable with a fixed-frequency rotator, it is not needed with the vernier rotator; similar rotation could be obtained with a longer, lower gradient rotation.

Note that the choice of second reference particle is somewhat arbitrary; the central particles of any other bunch could have been used, and the same results would be obtained, if proportional vernier offsets are used. The vernier offset ratio could also be changed from $\delta\lambda/N\lambda_{rf} = 0.1/10$ to something larger or smaller. A smaller value could enable a larger range of linear bunches, but require a longer rf rotation insert.

2.3 Discussion

In the above simulations we have used only one sign of muons in the capture and phase rotation, even though the initial target produces both μ^+ and μ^- in nearly equal amounts. Half-way between each of the stable phases for one sign of μ's, there is a stable phase for the opposite sign, and the same buncher would obtain strings of μ-bunches of both signs. The vernier rf rotation would also function similarly for both signs, and the combined buncher + rotator would produce trains of both μ^+ and μ^- bunches, 180° apart in phase, of similar intensities. This is unlike the low-frequency phase rotations of refs. [1-4], which can only capture one polarity.

In this initial example, we have arbitrarily set many system parameters, and these parameters can be greatly varied in future optimizations. We list some of these key parameters to invite consideration of variations:

1. *Drift:* The key parameter is the length of the section, z_0, which was arbitrarily set initially to 90m.
2. *Buncher*: The length of the section ($L_B = L_{tot} - z_0$), the bunching gradient $E_{rf}(z)$, the reference particle energy T_0, and $\delta(1/\beta)$ bunch spacing can be varied. The rf wavelength at the end of the buncher is $\lambda_{rf} = L_{tot}\, \delta(1/\beta)$.
3. *ϕ-δE rotation:* The length and rf voltage of the phase rotation section ($z_{R,final}$ and E_{rf}) are the key parameters. Also the reference particle energies (T_0, T_N) and the vernier parameter $\delta\lambda/(N\lambda_{rf})$ can be changed.
4. *Cooling System*: The effectiveness of the muon capture is finally determined by the match into the following cooling and /or acceleration systems. The key parameters of the cooling system are the rf frequency, the rf voltage, and the absorber energy loss rate, which set the longitudinal dynamics, and the transverse focusing, which determines the transverse cooling limits. These can be varied to improve overall performance.

In the initial example we have separated the adiabatic buncher and the ϕ-δE rotation into separated consecutive systems. It may be possible to combine these functions into a single system, or to design a more gradual transition between the two functions. It is not known whether that would improve or degrade performance from that of a separated design.

3. Review of 3-D simulations

The present system was first discussed in a simplified 1-D simulation of the longitudinal motion. It is recognized that that the low energy muons from a target have large transverse momenta, and therefore have largely nonparaxial motion. Also the nonlinear fields in the focusing magnets and the rf cavities can be important. The 3-D motion can be substantially different from that indicated by 1D simulations. Therefore, simulations in several 3-D codes have been initiated.

3.1 SIMUCOOL and ICOOL simulations

Initial 3-D simulations were obtained using A. Van Ginneken's simulation code SIMUCOOL.[7] In these simulations a constant solenoidal field of 1.25T was used for focusing, and rf cavities with sinusoidal wave forms were placed at 1m intervals in the buncher and 0.8m intervals in the ϕ-δE rotator.

Initial π-distributions were generated using the MARS particle production simulation code,[8] where production in a mercury target by a 24 GeV proton beam was assumed. The code SIMUCOOL was designed to track large numbers of particles, and that property was used in optimization, particularly in the ϕ-δE rotator. In these simulations it was noted that muon capture was somewhat improved by varying the rf frequency within the ϕ-δE rotation, and the large statistics was used to obtain a vernier-based optimum.

The SIMUCOOL simulations were then verified using the Muon Collaboration reference transport and cooling simulation code ICOOL,[9] where "more realistic" pillbox rf cavity models were used. The two codes produced nearly identical results.

In figs. 3A and 3B, we present longitudinal projections of μ-beam from SIMUCOOL simulations results, displaying beam at the end of the adiabatic buncher, (fig. 3A) and beam at the end of a vernier ϕ-δE rotation (fig. 3B). the beam is formed into a string of bunches by the adiabatic buncher and the bunches are "rotated" to obtain (nearly) equal central energies by the vernier ϕ-δE rotator.

3.2 GEANT4 simulations

Some simulations were also performed using Geant4[10] by Elvira and Keuss.[11, 12] Geant4 is designed to provide accurate and detailed 3-D simulations of particle motion through realistically determined electromagnetic fields that include all particle-material interactions. In the simulations, the magnetic fields are determined by current coils in the 3-D geometry (designed to obtain ~1.25T solenoidal fields.), and acceleration fields are determined by the electromagnetic fields in multicell pillbox cavities. Fig. 4 shows the geometry of a 6m segment of magnets with an rf cavity used in the simulations.

The simulations explored the question of the degree of granularity required for the bunching; that is, the number of different rf-frequency cavities required for multibunch formation. In initial simulations one cavity was placed in every meter of the buncher; this requires 60 rf frequencies. In simulations this was varied to 20 cavities (3m spacing), and 10 cavities (6m spacing). All three systems were able to provide adequate adiabatic bunching, with the 10-frequency case provided slightly inferior bunch formation. (This was in qualitative agreement with 1-D simulations, which showed no significant degradation in bunch formation until the number of cavities was reduced to ~12 or less.)

The bunching studies were followed by a successful simulation of fixed-frequency ϕ-δE rotation. Future simulations should include vernier ϕ-δE rotation, matching into a cooling channel, and reoptimization to determine accurate performance calculations.

3.3 ICOOL simulations with cooling

An accurate measure of the buncher-rotator effectiveness requires matching into the following cooling and acceleration systems, and accurate calculations of the resulting complete system performance. To do this properly, a complete cooling system must be designed which is matched to the output of the buncher-rotator and reoptimized to the desired cooling output. We have not yet developed a cooling system matched to this capture system.

However a 120m long cooling system was designed for the Study II neutrino factory [4] and simulated within ICOOL. To obtain an initial estimate of the possibility of matching into a cooling system, we simply took the output beam from the ICOOL simulation of the buncher rotator and inserted it into an ICOOL representation of the Study II cooling channel. This was not properly matched. The emittance of the beam exiting the buncher rotator was ε_T = 0.02m normalized, while the acceptance of the cooling channel was ε_T = 0.012m. (A matched cooler would start with initial cells that would cool ε_T from 0.02m to 0.012m.) Transverse motion and synchrotron motion was also not properly matched, and transverse-longitudinal correlations were not matched. (A partial transverse match was obtained by matching to 3T rather than 1.25T fields in the buncher-rotator.) The central energy and rf phase were reoptimized to match.

Even with the gross mismatches, the ICOOL simulation results were encouraging. ~40% of the μ's are lost in the initial few cells of the cooling channel, corresponding to the mismatch in acceptances. Following that initial loss, the cooling and losses are very similar to those obtained with the Study 2 beam.

If we start with μ^+ obtained from π^+ produced at a Hg target from 24 GeV protons at the beginning (initial distributions from MARS simulations) of the drift-buncher-rotator, we obtain ~0.22 cooled μ^+/p at the end of the Study II cooling channel. This was only ~5% less than that obtained in parallel ICOOL simulations (starting from the same π^+'s) of the complete Study II system. The complete Study II system included a sequence of 3 induction linacs for nondistorting phase-energy rotation, a "minicool" initial cooler, and a buncher matching the beam into the cooling channel. (We note here that the Study II system obtains only one sign of μ's, but the new buncher-rotator-cooler would also produce a nearly equal number of opposite sign μ^-'s.) Figs. 5A and 5B display the longitudinal phase space distributions after the complete Study II system and after the present buncher rotator scenario using the Study II cooling channel.

The muon acceptance is reduced to ~0.16 μ^+/p if the buncher-rotator field is at 1.25T and not matched to 3T (The transverse motion is more mismatched.). Acceptance also appears to be reduced if a fixed-frequency rotation be used rather than the vernier rotation. The results indicate the desirability of properly matched motion, and it is likely that a properly designed and matched cooling channel would provide even more success in μ acceptance.

3.4 Comments

All of these 3-D simulations have developed results consistent with those obtained within 1-D simulations, which may indicate that transverse motion effects are not too important and that 1-D simulation studies could be quite useful in determining initial design parameters for future systems. This hypothesis requires further verification.

4. Variations and future directions

The initial example was developed in order to match the Study II neutrino factory design, which uses a long train (~100m long) of ~200 MHz bunches to match into a ~200 MHz cooling and acceleration design. The same procedure can be readily adapted to obtain bunches at other frequencies (50, 100, 200, or 400 MHz, etc.) and to obtain longer or shorter bunch trains. (1-D simulations of these variants have been developed.) The general utility indicates that the method could be used to develop μ-bunches for any neutrino factory scenario, including the CERN and JHF neutrino factory scenarios [13, 14].

The method may also be adaptable to the somewhat different requirements of a μ^+-μ^- Collider. For a high-luminosity collider, we require a small number of both μ^+ and μ^- bunches. The method does produce both μ^+ and μ^- bunches, but would tend to produce a large number of bunches. Scenarios with a more limited number of initial bunches, plus some bunch combination in the cooling process, may be suited to a collider; appropriate methods should be developed.

References

[1] C. Ankenbrandt et al., PRST Accel. Beams 2, 081001 (1999).
[2] *Muon-Muon Collider – a Feasibility Study*, BNL-52503, Fermilab Conf-96/002, LBNL-38946 (1996).
[3] 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).
[4] S. Ozaki, R. Palmer, M. S. Zisman, Editors, *Feasibility Study-II of a Muon-Based Neutrino Source*, BNL-52623, June 2001. http://www.cap.bnl.gov/mumu/studyII/FS2-report.html.
[5] D. Neuffer, "High Frequency Buncher and Phase Rotation for the Muon Source", MuCOOL Note 181, October 2000.
[6] D. Neuffer and A. Van Ginneken, Proc. 2001 Particle Accelerator Conference, Chicago, P. 2029 (2001).
[7] A. Van Ginneken, "Adiabatic and Vernier Bunching in Decay Channel", MuCOOL Note 220, October 2001.
[8] N. Mokhov, "Particle Production and Radiation Environment at a Neutrino Factory Target Station", Fermilab-Conf-01/134, Proc. 2001 Particle Accelerator Conference, Chicago, P. 745 (2001), see http://www-ap.fnal.gov/MARS/.
[9] R. Fernow, "ICOOL, a Simulation Code for Ionization Cooling of Muon Beams", Proc. 1999 Particle Accelerator Conference, New York, p. 3020 (1999), see http://pubweb.bnl.gov/people/fernow/.
[10] V. Daniel Elvira, P. Lebrun, P. Spentzouris, "Beam Simulation Tools for GEANT4 (BT-v1.0) User's Guide", MuCOOL Note 260, October 2002.
[11] V. Daniel Elvira, "High Frequency Adiabatic Buncher (Geant4 Simulation)", MuCOOL Note 253, September 2002.
[12] N. Keuss and V. Daniel Elvira, "Fixed Frequency Phase Rotator for the Neutrino Factory (Geant4 Simulation)", MuCOOL Note 254, September 2002.
[13] NuFactJ Working Group, "A Feasibility study of a Neutrino factory in Japan", May 2001.
[14] Y. Mori, "Neutrino factory in Japan" Submitted to Proc. NuFACT02, Oxford (2002)

Figure 1: Schematic view of the components of the system, showing an initial drift, the varying frequency buncher, and the phase-energy (ϕ-δE) rotator leading into a cooling section. π's would be produced by protons on a target at the beginning of the drift, decay to μ's in the drift, while lengthening in phase the buncher and ϕ-δE rotator form the μ's into a string of bunches matched into the cooler.

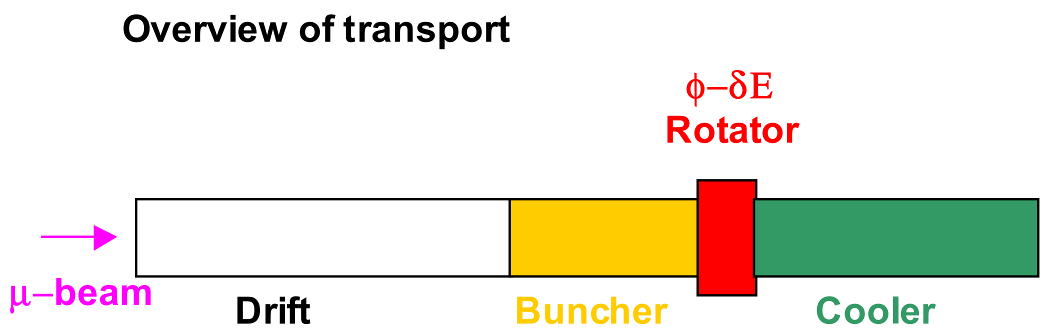

Figure 2A This displays a simulated muon beam after a 90m drift. The initial beam has an energy spread of ±85 MeV about a central reference energy of T_0 = 125 MeV, and a small initial longitudinal spread (0.6m). Horizontal scale is 0 to 0.30 GeV; vertical is-20 to 60m.

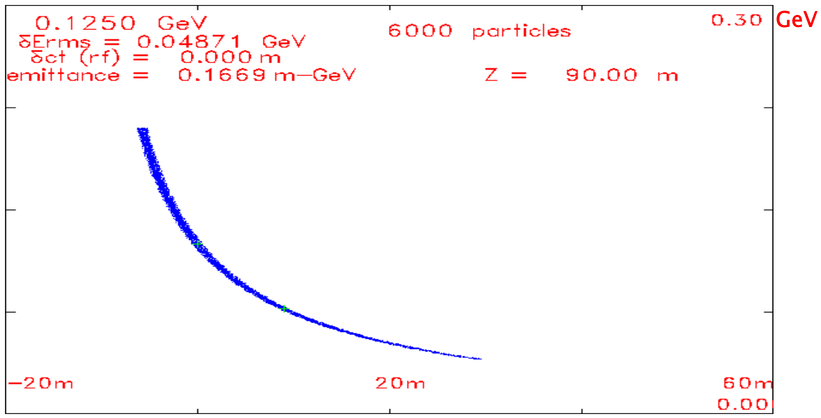

Figure 2B. μ-beam after the 90m drift and a 60m adiabatic buncher with $\delta(1/\beta)$ =0.01. The rf gradient E_{rf} (z) increases quadratically from 0 to 4.8 MV/m.

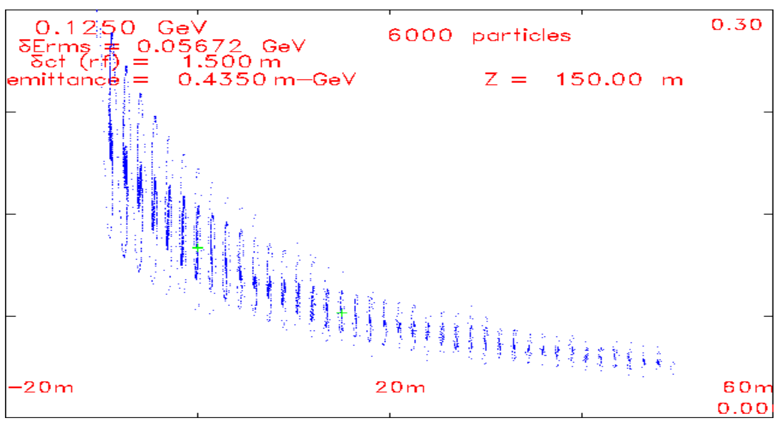

Figure 2C. μ-beam after the vernier rf rotation(+7.84m long). The initial reference bunches are at 0 and $10\lambda_{rf}$ with energies of 125 and 77.281 MeV; the vernier parameter is $\delta\lambda/10\lambda_{rf}$ =0.1, and the rf gradient was E_{rf}= 10 MV/m. The initial energy spread has been formed into a string of ~40 bunches.

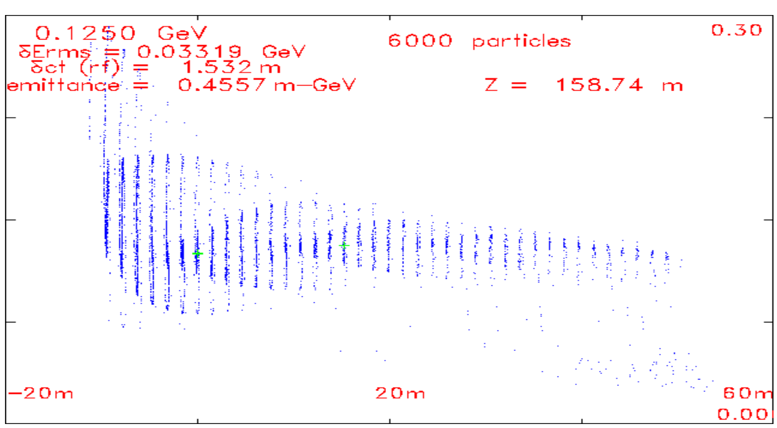

Figure 3A: SIMUCOOL simulation results of beam at the end of a 100m drift +60m adiabatic buncher. The beam is initially generated at the target from MARS simulations of 24 GeV protons on a Hg target. It is then propagated through a drift + an adiabatic buncher forming the beam into a string of ~200 MHz bunches.

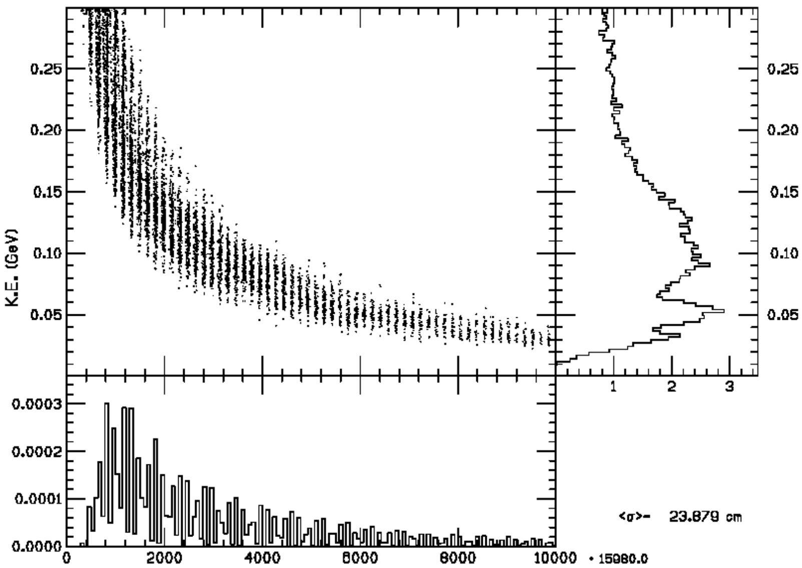

Figure 3B: SIMUCOOL simulation results of beam at the end of a vernier ϕ-δE rotation. The bunches of the previous simulation are lined up with (nearly) equal central momenta.

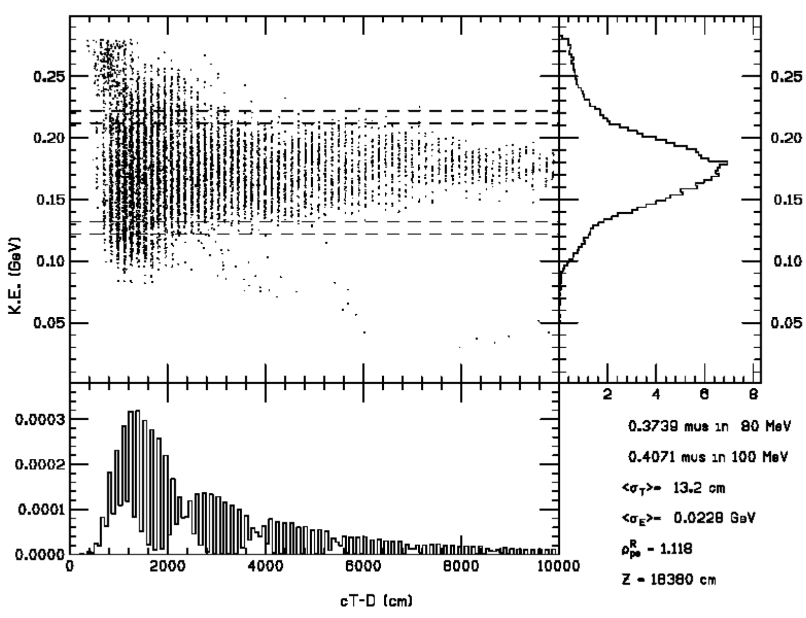

Figure 4. Geometry of a buncher segment as developed for the GEANT4 simulations. The 6m segment includes 4 current coils to produce the 1.25T solenoidal field and 6 pillbox rf cavities in the center (to form a 6-cell cavity). The coil radius is at 0.6m.

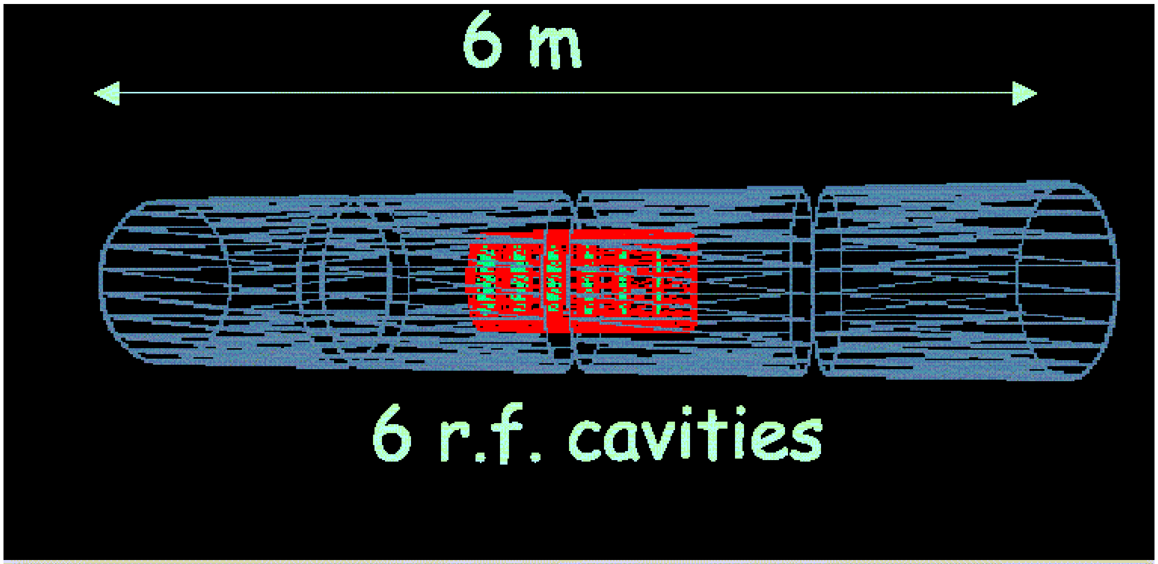

Figure 5A. Longitudinal projection of surviving muon beam after ICOOL simulation of the Study II induction linac phase-energy rotation, minicooler, buncher, and cooling channel. ~1600 μ^+'s out of an initial distribution of 8000 π^+'s survive to the end of the channel. (With 1.15 π^+'s produced per proton, this corresponds to ~0.23 μ^+/p.)

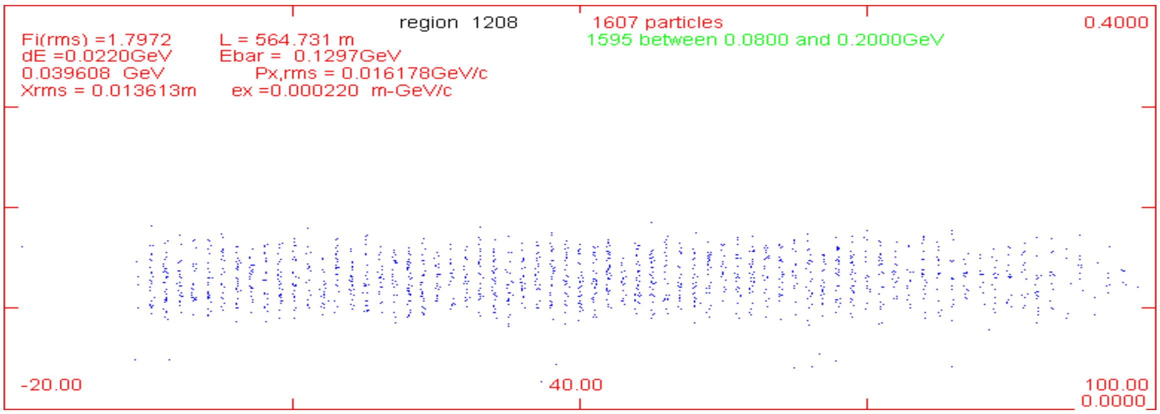

Figure 5B. Longitudinal projection of surviving muon beam after ICOOL simulation of a drift, 60m adiabatic buncher, and vernier ϕ-δE rotation, mismatched and propagated through the Study II cooling channel. ~1530 μ^+'s out of an initial distribution of 8000 π^+'s survive to the end of the channel. (With 1.15 π^+'s produced per proton, this corresponds to ~0.22 μ^+/p.) The same initial π's were used in Figs. 5A and 5B. Both simulations obtain similar bunch trains with similar longitudinal and transverse emittances, although the Fig. 5A bunch train is longer and more evenly populated.