MuCool Note 324

Gas-filled rf Cavites and Neutrino Factory High-Frequency Phase Rotation

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Abstract. A scenario for capture, bunching, and phase-energy rotation with cooling of μ's from a proton source is explored. It requires a drift section, a bunching section and a ϕ-δE rotation section with a gas-filled transport. The rf frequency changes along the transport in order to form the μ's into a train of equal-energy bunches suitable for acceleration. The gas-filled transport also cools the beam. As in the previous scheme with vacuum cavities,[1] the method simultaneously captures and cools positive and negative muons.

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 neutrino factory design studies, this beam is transformed into a longer string of bunches with relatively smaller energy spread.

In the neutrino factory design study 2A,[4, 5, 6] the π's first 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. (see Fig. 1) 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, in that study). This forms the beam into a string of bunches of differing energies. Following the buncher, the beam is transported through an "rf rotator" section that performs a phase-energy rotation that aligns the μ bunches to (nearly) equal central energies, suitable for injection into a fixed-frequency ~200 MHz cooling system, and subsequent acceleration. Fig. 1 shows a schematic overview of this system.

In study 2A, the rf cavities are conventional vacuum-filled pillbox cavities, with Be windows in the final version of the phase rotator. Recently it has been proposed that gas-filled rf cavites could be used for acceleration and cooling of muons.[7, 8] High-pressure gas can suppress breakdown, possibly enabling higher gradient, and the gas can provide energy-loss cooling. R.Fernow and J. Gallardo considered using gas-filled cavities in the cooling system[9].

In the present paper we start with the Study 2A bunching and phase rotation layout, but use gas-filled rf cavities in the phase rotation region. The rf gradient is increased to compensate for the energy loss in the gas, and the system cooling and acceptance is studied.

Study 2A Baseline Example

For simplicity we start with the initial ICOOL[10] data version presented by Palmer in December 2003, from which the final Study 2A version was developed.[5] (We are not initially using the final "fully-realistic" version of Study 2A in order to avoid complexity.) 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.

The system consists of 0.75m long cells with 0.5m long cavities and 0.25m long drifts. In the buncher the rf gradient in the cavities increases following $V_{rf}' = 3\ (z/L) + 9\ (z/L)^2$ MV/m, where z is distance along the buncher, and L is the length of the buncher. The rf frequency decreases from 337.5 MHz to 232 MHz along the buncher, following a rule where the reference particles (at $P_\mu = 280$ and 154 MeV/c) remain separated by 18 rf wavelengths.

In the phase-energy rotator, the reference particles are separated by 18.05 rf wavelengths, so that the front end bunches are accelerated 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 during .sections the bunches are lined up in nearly equal energies with the reference ~201.25MHz spacing.

At the end of this section the beam is transversely matched from 2T into 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 had two 1cm LiH absorbers, so the baseline energy loss per ce11 was 2 × 1.59 MeV= 3.18 MeV/cell. Over an 81m length (108 cells) 343.44 MeV of energy loss occurs.

The Study 2A initial example obtains ~0.23 μ/p within the study 2a reference acceptances (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 $\varepsilon_\perp$ < 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. At an intermediate distance (with 35m cooling) the acceptance is 0.179 and .074, and the rms transverse emittance is 0.0116.

The ICOOL simulation results are displayed graphically in Fig. 2 and 3. The longitudinal capture efficiency is shown in fig. 2 while the transverse emittance cooling is shown in fig. 3.

Initial Gas-Cavity Phase-Rotator-Cooler Examples

Starting from the baseline example, a series of runs was attempted in which the vacuum in the phase rotator and the cooling region was replaced by gas-filled cavities. The baseline energy loss in gaseous hydrogen is dE/dx = 0.000344 P MeV/cm, where P is the pressure in atmospheres (at a temperature of 295° K).[11] In the examples below we (initially) use a pressure of 133atm averaged in this section, 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.

Initially, the vacuum in only the phase-rotator cavities was replaced by 200atm of gas, with the drifts remaining as vacuum. The rf voltage within the phase-rotator was raised to compensate for the added energy loss in the rotator, to 20MV/m, and the reference phase moved to 20°. With this configuration ~0.2 μ/p appeared within the Study 2A acceptance (of $\varepsilon_\perp$ = 0.03m) at the end of the rotator, in ICOOL simulation, and the rms emittance was cooled to ~0.01m.

In the ICOOL simulations the rotator was followed by ~30m of the (alternating solenoid) Study 2A cooling channel. This section was used to test whether the rotated beam was properly matched, and whether further Study 2A cooling would be helpful. Matching from 2T into an alternating solenoid lattice at the end of the ϕ-E rotator reduced the acceptance by ~10%, while increasing rms emittance by ~10%.

The gas was then extended throughout the cells (cavity + drift) and the pressure reduced to 133atm, obtaining the same mean energy loss per cell. (At this time we noticed an unexpected feature of ICOOL. Energy loss of reference particles in material occurs in drift regions but not within rf cavities. This feature was then properly compensated.) Similar simulation results were obtained.

The mismatch problem was compensated by moving the transverse matching (that matches from 2T to the alternating solenoid lattice) to the end of the buncher (at ~160m from the target). The ϕ-E rotation with gas cooling then occurs within an alternating solenoid focusing system.

With these modifications we obtained an initial gas cavity ϕ-E rotator system which was nearly as successful in phase-energy rotation and cooling as the complete Study 2A system. The new system removes the separate cooling channel from the neutrino factory system.

ICOOL simulation results are presented in Figs. 2, 3, and 4.

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

The rms longitudinal emittance of the beam at this point is ~0.073. The μ acceptance could be slightly improved by increasing the longitudinal emittance acceptance. If the longitudinal emittance aperture were increased to 0.2m, then μ/p at $\varepsilon_\perp$ <0.03 increase to 0.212, with 0.106 at $\varepsilon_\perp$ <0.015.

In these particular simulations, a continuation of the Study 2A cooling channel beyond the rotator did not lead to great improvements in the accepted muons An additional 30m of cooling increased the baseline aperture acceptance to ~0.207 and the restricted aperture acceptance to ~0.112, while cooling the transverse emittance to ~0.0079m. For larger improvements we may need a different cooling channel, possibly with stronger focusing and/or longitudinal cooling.

This first example is not completely reoptimized and matching (longitudinal and transverse) could be improved. The general result is that the projected performance is at least similar to that obtained with the complete Study 2A system, with the potential advantage that the separate cooling channel (~80m of high-gradient rf and solenoidal focusing) can be removed without significant loss in performance. The ϕ-E rotator section would operate at somewhat larger gradients. Total rf power requirements would still be somewhat reduced.

Comments on First Example

In this initial gas-cavity example, we have arbitrarily set many system parameters, and these parameters can be greatly varied in other 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 to 111 m., following the example of Study 2A
2. *Buncher*: The length of the section (L_B), the bunching gradient $E_{rf}(z)$, the reference particle momenta, and the bunch spacing between reference particles can be varied.
3. *ϕ-δE Rotation with Cooling:* The length and rf voltage of the phase rotation section (L_R and E_{rf}) are key parameters. Also the reference particle energies (T_0, T_N) and the vernier parameter $\delta\lambda/(N\lambda_{rf})$ can be changed. (0.05 was used in this example). The gas density can be reoptimized. The transverse focusing could be modified to increase the cooling and/or improve matching and avoid instabilities.

The present parameters are designed to match into a downstream ~201.25 MHz acceleration system. This fundamental parameter could be modified to fit other scenarios (i. e., 30, 88, 200, 400 … MHz systems).

In this initial gas-cavity system, the adiabatic buncher has vacuum cavities and the ϕ-δE rotation section has gas cavities, incorporating cooling. It is also possible to combine these functions into a single system, or to design a more gradual transition between the two functions.

Conclusions and Discussion

This initial example demonstrates that 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.

Acknowledgments

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Figure 1: Layout of Study 2A 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 and cooled transversely within the 80m long cooling section. In the present paper we consider using gas-filled cavities to obtain cooling in the rf rotator, eliminating the need for an 80m cooling channel.

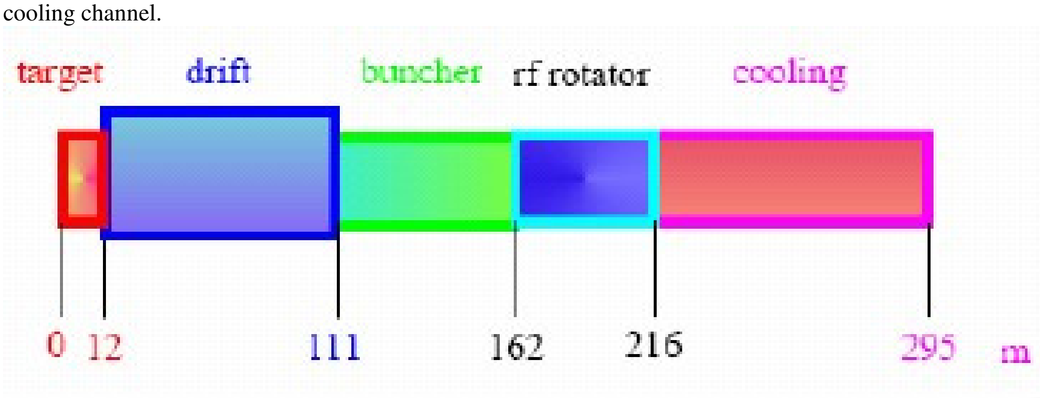


Figure 2A: All muons and muons accepted within the design transverse amplitudes of 0.015 and 0.03m and the design rf buckets for the baseline Study 2A example of 12/2003.

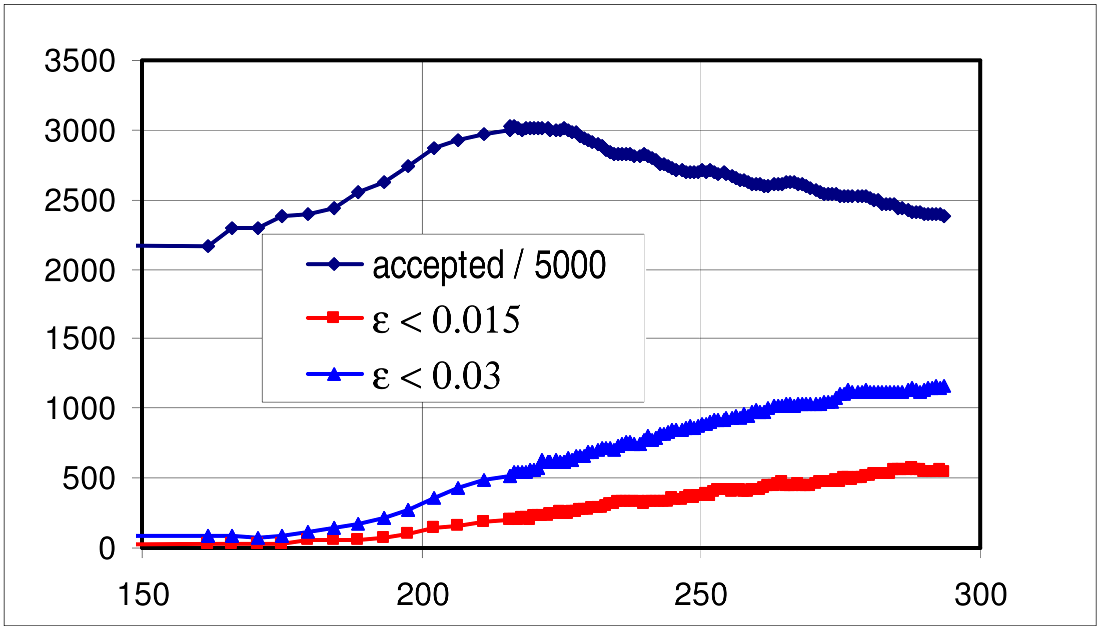


Figure 2B: All muons and muons accepted within the design transverse amplitudes of 0.015 and 0.03m and the design rf buckets for the baseline Study 2A example of 12/2003. Acceptance rises to .2 μ/p after phase rotation and cooling

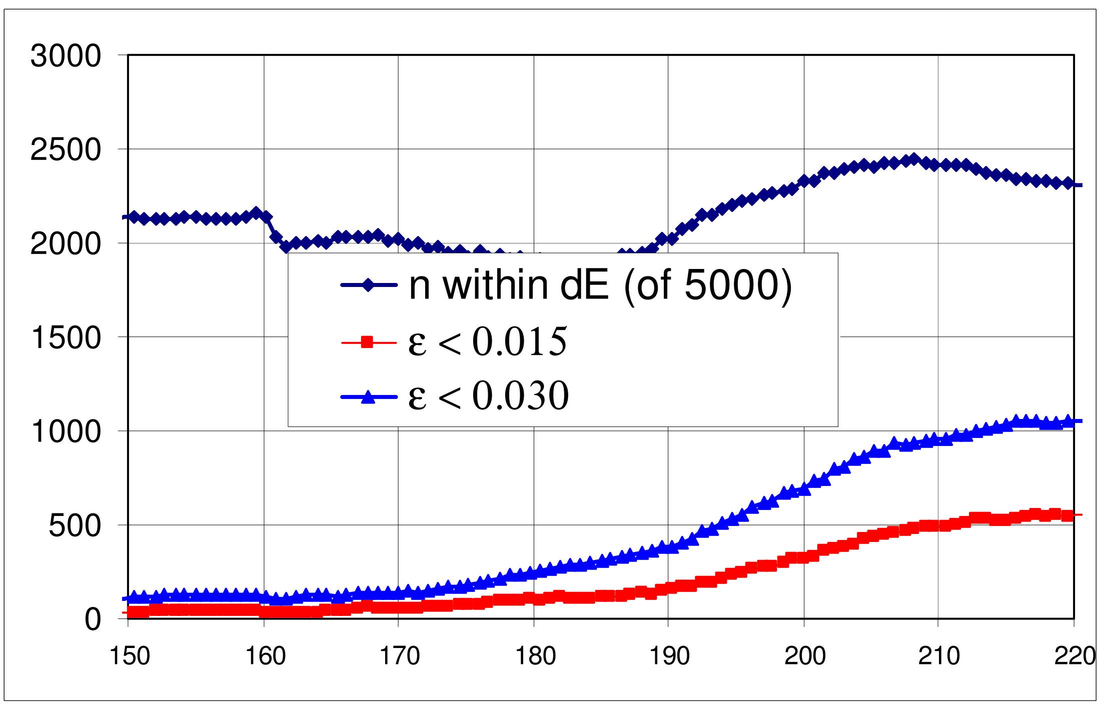


Figure 3A: Transverse emittance cooling in the cooling channel for study 2A: The transverse emittance is cooled from ~0.018m to ~0.08m over an 80m cooling channel following the bunching and phase rotation.

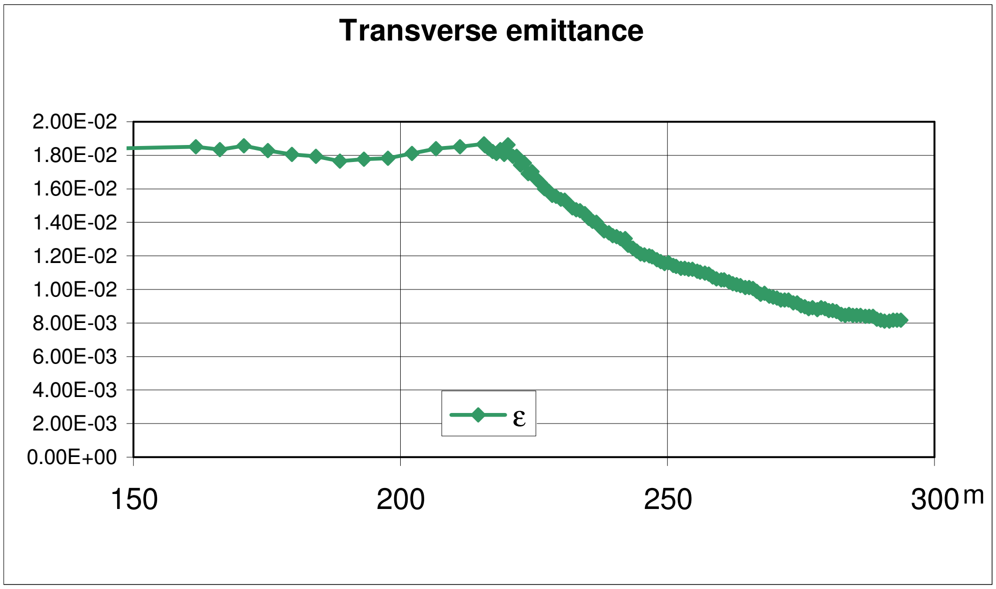


Figure 3B: Transverse emittance cooling with gas-filled phase rotation cavities: The transverse emittance is cooled from ~0.019m to ~0.09m over the ~54m ϕ-E rotation and cooling channel following the buncher: the separate cooling channel is not required.

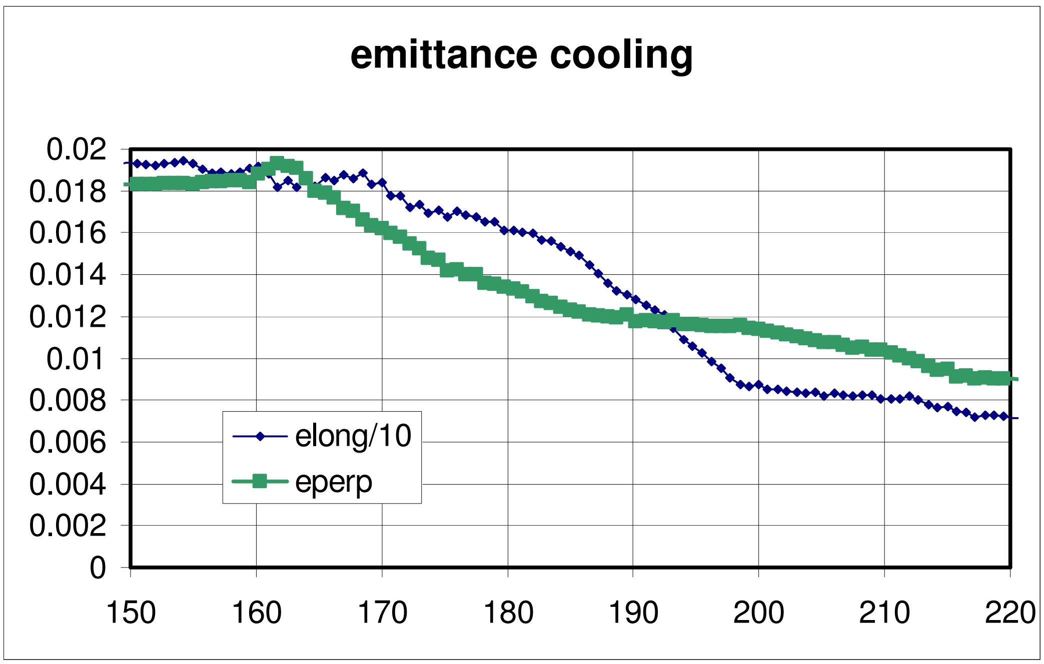
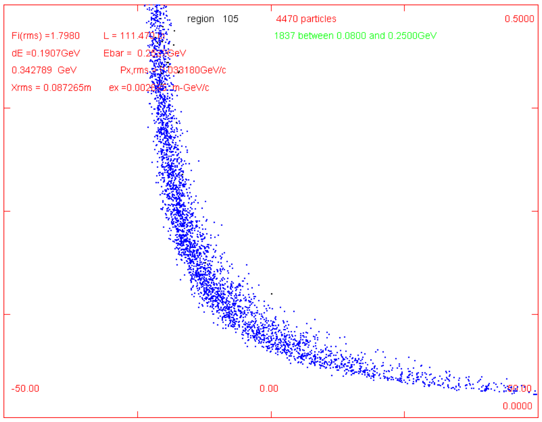
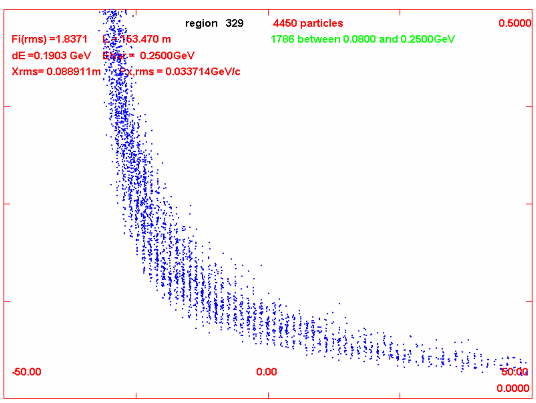


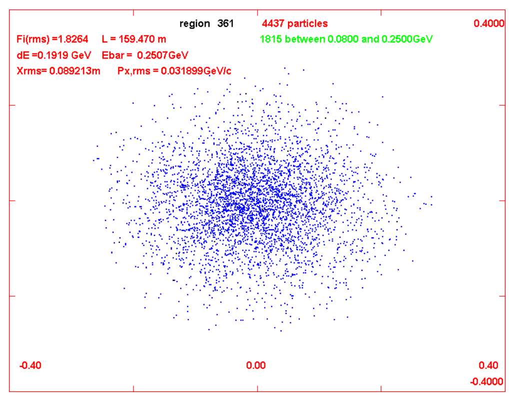
Figure 4: ICOOL simulation results of the buncher and phase rotation with gas-cavity cooling, at the parameters of the example described in the text. Figure A: μ's at z=110m; end of drift section B: μ's at z=162m, the end of the buncher. The beam has been formed into a string of ~200MHz bunches at different 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).



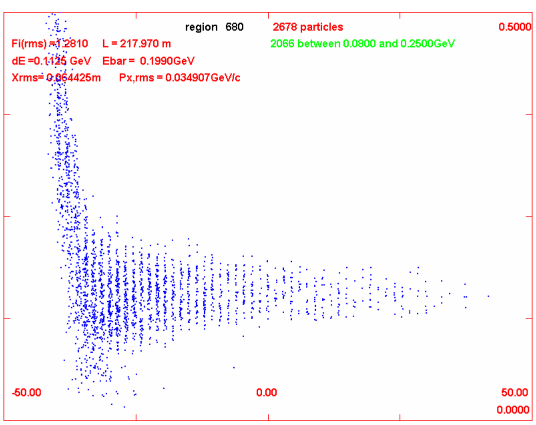
A: L=111m, (after drift)



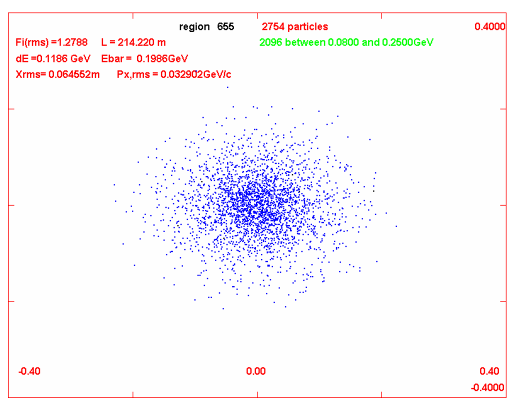
B: L=163m (after buncher)



BT: x-y beam before cooling



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



CT: x-y beam after cooling and rotation.