11/29/1999

**Subject: Longitudinal Injection Scenarios for SNS**
**From: John Galambos**

The present SNS longitudinal injection scenario calls for chopping a 35% gap from each 841 ns linac mini-pulse in order to create a 250 ns extraction gap in the accumulated beam in the ring. This gap length is required to allow sufficient time for the extraction kickers to fully energize and keep losses low at extraction. In this note, scenarios are presented with injection chopper gaps as low as 20%, which also attain a 250 ns clean gap at the time of beam extraction. Reducing the chopped portion of the injected beam offers the possibility of increased beam power for a given ion source performance, and ring accumulation period. For instance, injecting with a 20% chopped gap instead of the nominal 35% gap offers a 23% beam power increase, or equivalently offers the possibility of achieving the nominal beam power with a 23% lower ion source current. Combinations of the following techniques are used to attain a 250 ns extraction gap with smaller chopped portions of the injected beam:

1. Ramping the RF buncher voltage.
2. Increasing the chopped gap length near the end of injection.
3. Letting the accumulated beam spin some additional turns after particle injection.
4.

Other sensitivities investigated here are use of higher RF voltages than the nominal 40 kV, use of a truncated gaussian injection energy distribution instead of the present nominal uniform energy distribution, and use of a single harmonic RF waveform vs. the nominal dual harmonic.

The ORBIT macro-particle tracking code [1] is used to model the longitudinal transport here. All cases use 100,000 macro-particles and 64 bins for the space charge FFT calculation. A benchmark calculation of the SNS injection with the ANL code capture_spc shows very good agreement [2]. Only the longitudinal transport is considered here, unless noted otherwise.

**Nominal Injection Scenario**

*Case 1: constant chopper gap, constant RF voltage*

For comparison purposes, the presently prescribed nominal longitudinal injection scenario is described first. Table 1 lists some of the assumptions used here for modeling this scenario. These values are used throughout, unless stated otherwise. Some beam parameters at extraction for this case are listed as case 1 in Table 2. Three calculated extraction parameters are concentrated on. First the extraction gap length, defined here as the length which contains $< 10^{-4}$ of the beam is listed. This gap is required to be at least 250 ns in order to provide an adequate time period for the extraction gap kicker magnets to energize. Second the bunch factor, which affects the magnitude of the transverse space charge effects, is monitored. Finally the accumulated beam energy spread is shown, as this spread is a measure of the beam's robustness to instabilities. Figure 1 shows the beam distribution in longitudinal phase space at several times during the injection, for the nominal injection scenario.

Table 1. Present nominal longitudinal injection parameters for SNS.

| | |
|---|---|
| Injection gap length | 35% of ring, or 294 ns |
| Injection distribution | Uniform, ± 4 MeV, centroid at 1000 MeV |
| RF type | Dual harmonic |
| RF voltage (kV) | 40 kV primary, 20 kV secondary |
| Injection turns | 1158 |
| Additional turns after injection | 1-10 to synchronize extraction with the neutron chopper |

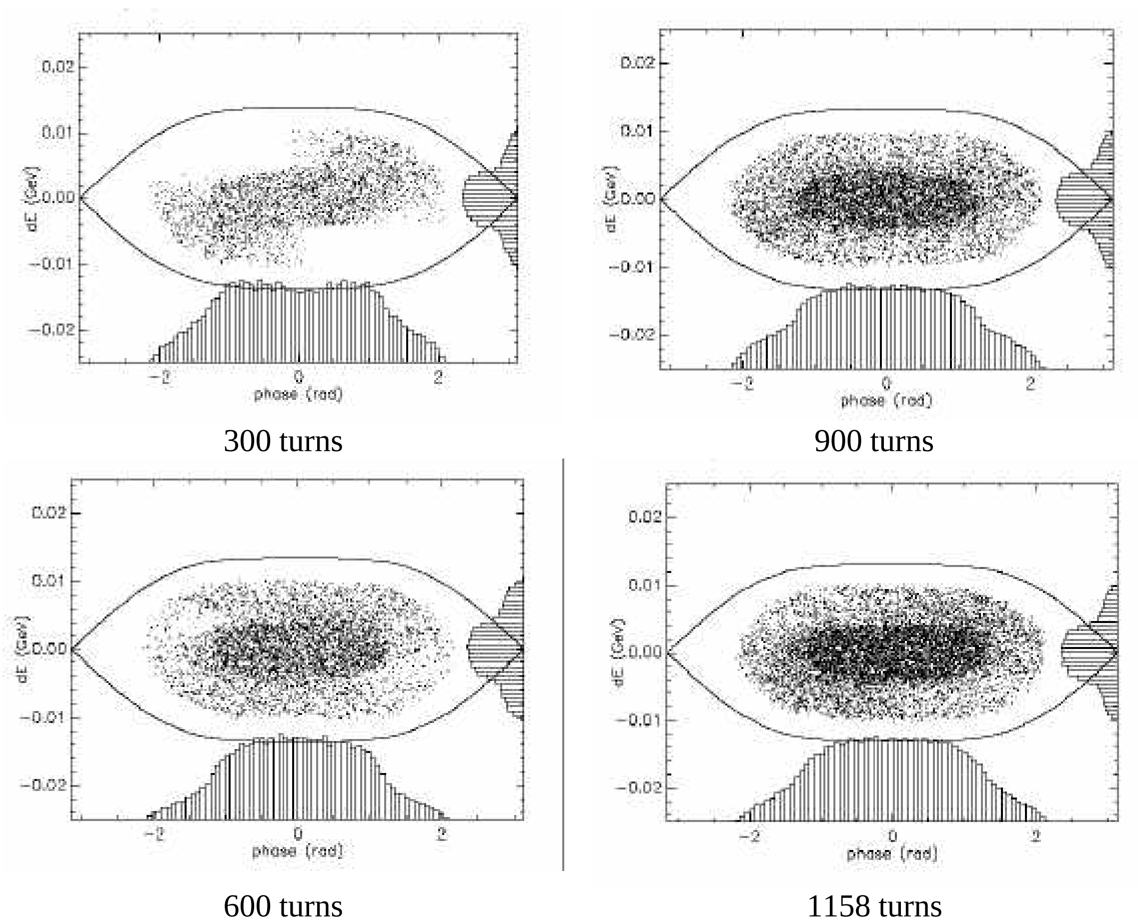



Figure 1. Phase space plots during the beam accumulation period for the present nominal injection scenario.

Table 2. Alternate longitudinal injection scenario parameters.

| Case: | Injection parameters: RF voltage (1) Start | RF voltage (1) End | Injection gap | Spin turns (2) | Extraction parameters: Gap length (ns) (3) | Bunch factor | *(dE/E)*$_{RMS}$ (%) (4) |
|---|---|---|---|---|---|---|---|
| *Dual harmonic RF*: | | | | | | | |
| 1) Present nominal | 40 | 40 | 35% throughout | 0 | 258 | 0.446 | 0.273 |
| 2) Ramp RF | 10 | 40 | 25%, ramped to 40% last 150 turns | 50 | 257 | 0.483 | 0.286 |
| 3) Use gaussian linac E distribution (5) | 10 | 40 | 22%, ramped to 40% last 150 turns | 40 | 255 | 0.448 | 0.278 |
| 4) 60 kV RF, truncated gaussian | 10 | 60 | 20%, ramped to 40% last 150 turns | 10 | 250 | 0.448 | 0.353 |
| *Single harmonic RF*: | | | | | | | |
| 5) 40 kV, truncated gaussian | 10 | 40 | 26%, ramped to 40% last 200 turns | 70 | 252 | 0.320 | 0.319 |
| 6) 60 kV, truncated gaussian | 15 | 60 | 20%, ramped to 40% last 200 turns | 55 | 253 | 0.310 | 0.437 |

Notes for Table 2:

(1) For the dual harmonic cases, the second harmonic RF level is held fixed at 50% of the primary. The RF waveforms are taken as linear here, between the value listed for the start of injection to that listed for the end of injection. If additional spin turns are employed, the RF level at the end of injection is held constant during this period.

(2) Additional turns after the end of particle injection and before extraction.

(3) Length of the gap which contains < $10^{-4}$ of the beam.

(4) RMS value of the entire accumulated beam at extraction.

(5) The energy distribution from the HEBT is taken to be a gaussian with $\sigma$ = 1.5 MeV, truncated beyond $\delta E = \pm 4$ MeV.

**Adiabatic Capture Injection Scenarios**

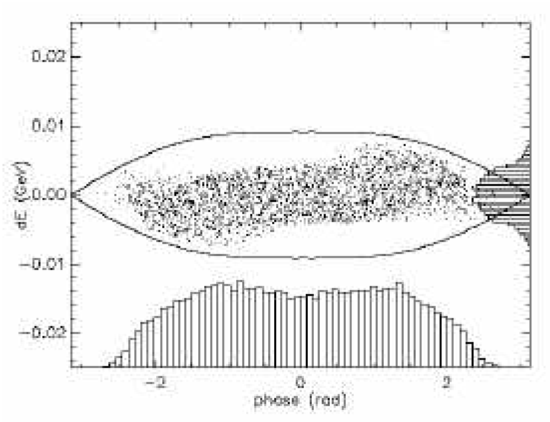
*Case 2: dual harmonic, 40 kV RF, uniform energy injection*

Figure 2 shows the longitudinal phase space plots for a case with an injection gap of 25% as opposed to the nominal 35% injection gap. The gap is kept at 25% for turns 1 through 1008, and ramped linearly to 40% from turns 1009 through 1158. Also the RF voltage is ramped linearly from 10 to 40 kV throughout the injection. Finally, the injected beam is allowed to spin an additional 50 turns prior to extraction (from turns 1159 to 1208) with no further particle injection. The nominal uniform injection distribution from the HEBT is used here. This is “case 2” in Table 2. A comparable gap length, bunch factor and beam energy spread at extraction are attained as for the nominal case, despite injecting with a smaller chopped gap throughout most of the injection.

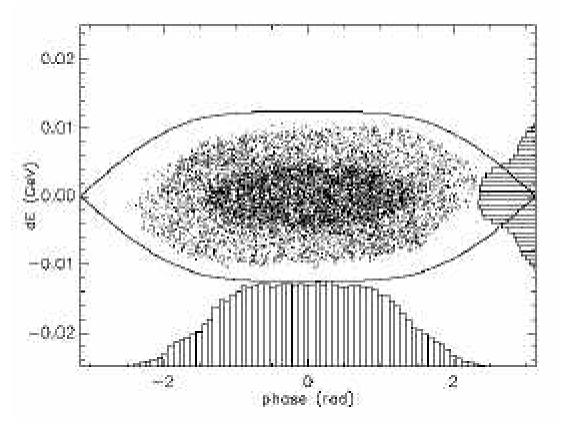
Examination of Fig. 2 reveals how the 250 ns extraction gap is recouped in this case. Increasing the RF voltage throughout injection causes the particles to traverse longitudinal phase space with smaller orbits as time progresses, resulting in a noticeable slant in the top and bottom of the bunch. This causes the particles injected at a large phase angle (i.e. near the gap) to end up at a smaller phase angle after one half of a synchrotron oscillation, effectively regaining some gap. This is evident near turn 1008 in Fig. 2. Even though by turn 1008 the particles injected early on have a smaller phase angle after ½ a synchrotron oscillation, the recently injected particles have not had time to orbit out of the 250 ns gap. In order to start clearing the recently injected particles the chopper width is increased from 25% to 40% over the final 150 turns. This offers a noticeable reduction of particles beyond $\pm$ 2 rad between turns 1008 and 1158 as shown in Figure 2. However, ~ $10^{-3}$ of the beam remains within the 250 ns extraction gap at the end of particle injection (turn 1158). Allowing the beam to spin ~ 50 more turns, without further particle injection, permits the remaining portion of beam in the 250 ns gap to further reduce. Figure 3 shows the length of the gap containing < 0.01% of the beam vs. the number of additional non-injection spin turns. After ~ 50 spin turns, the 250 ns gap length is attained for this case.

The technique of ramping the RF voltage during the injection process is similar to that proposed elsewhere, for example in the IPNS upgrade study [3] and is called adiabatic capture. Ramping the RF voltage during injection is also the standard RF waveform employed in operation of the PSR.

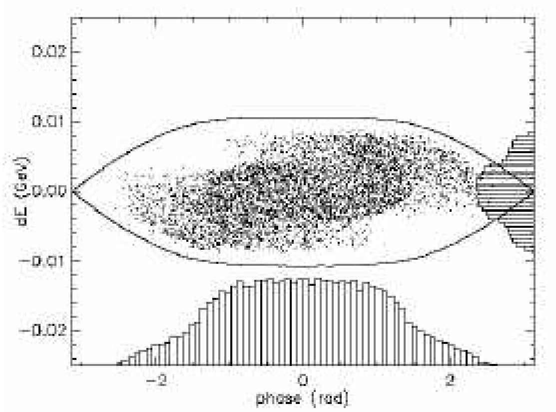
In the following sections the sensitivity of the longitudinal injection to several assumptions listed in Table 1 is examined. For each sensitivity the RF voltage ramp during injection, the chopper gap ramp near the end of injection, and the number of additional non-injection spin turns after injection are varied to achieve a 250 ns extraction gap, for as small a chopper gap as possible.



Turn 300



Turn 1008



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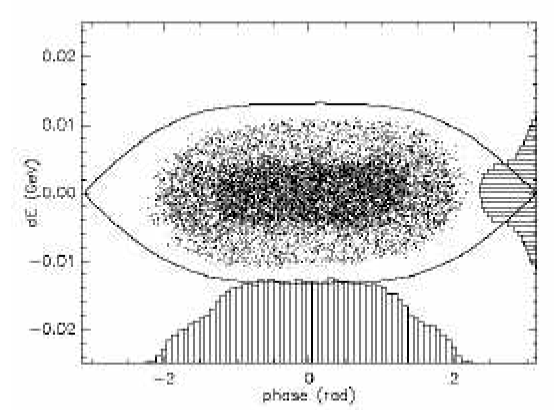
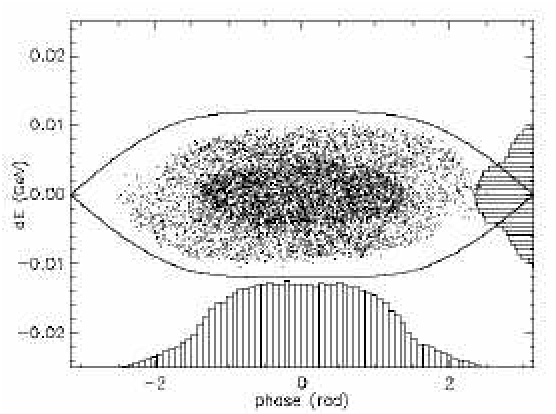
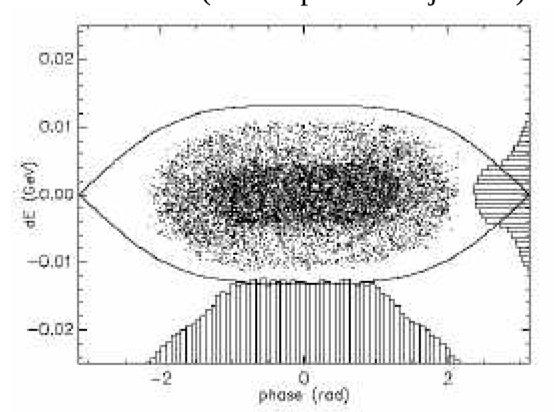


Turn 1158 (end of particle injection)



Turn 900



Turn 1208 (extraction)

Figure 2. Phase space plots during the beam accumulation period for an adiabatic capture injection scenario, using 40 kV dual harmonic RF.

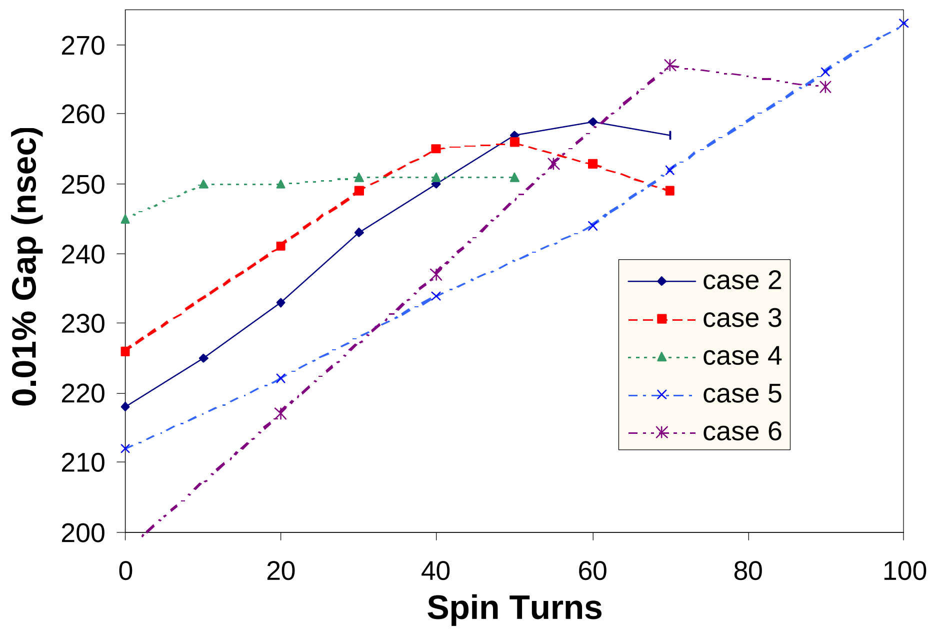



Figure 3 Gap length containing < $10^{-4}$ of the beam vs. additional spin turns, with no injection, after the 1158 injection turns.

*Case 3: Dual Harmonic, 40 kV RF, gaussian energy injection*

Figure 4a shows the uniform injection energy distribution between 996 and 1004 MeV, as used in the nominal scenario. The RF bucket in this figure has a primary harmonic of 10 kV, corresponding to the start of the injection scenario in "case 2" above. This bucket grows throughout the injection cycle as the RF voltage is ramped. Figure 4b shows an alternative injection distribution, which is more peaked about the centroid injection energy of 1 GeV, and has the same RF bucket. This latter distribution is gaussian with a standard deviation of 1.5 MeV, and truncated beyond 996 and 1004 MeV. Use of a more peaked injection distribution allows injection with a smaller gap throughout the beam accumulation period, as indicated in "case 3" in Table 2. Here, a 22% injection gap is possible while retaining the 250 ns gap at extraction, using a similar strategy as described above. The RMS energy spread of the accumulated beam in the ring similar to that for the nominal case, despite the fact that the injection distribution has a smaller RMS energy spread. As seen in Fig. 3, fewer spin turns are required for the $10^{-4}$ gap to reach 250 ns than for the above case. This truncated gaussian distribution is used in subsequent sensitivities.

The ratio of the bucket area to bunch area is close to unity at the start of injection, as shown in Fig. 4. These buckets are for the start of injection, when the RF voltage is smallest. However, as seen in Fig. 2, the bucket to bunch area ratio is larger towards the end of injection. Even if a particle falls outside the bucket early on, it has a good chance of being recaptured by the expanding bucket. The important parameter regarding longitudinal loss of beam is the amount of beam in the gap at extraction. It is this parameter that is minimized in this study, not the amount of beam in the gap early on.

*Case 4: dual harmonic, 60 kV RF*

Here the benefit of allowing higher RF voltages is examined, namely using 60 kV for the primary RF harmonic and 30 kV for the secondary RF harmonic. Case 4 in Table 2 shows optimized injection parameters for this case. A 20% injection gap is possible with a peak RF voltage of 60 kV. Because of the increased RF voltage, the RMS energy spread of the accumulated beam is larger. Also, it is not necessary to let the beam spin as long after injection, for the $10^{-4}$ gap to reach 250 ns, as seen in Fig. 4. Use of 60 kV RF does not offer a significant advantage over 40 kV with regards to using a smaller chopped gap or attaining a higher bunch factor.

*Case 5: single harmonic, 40 kV RF*

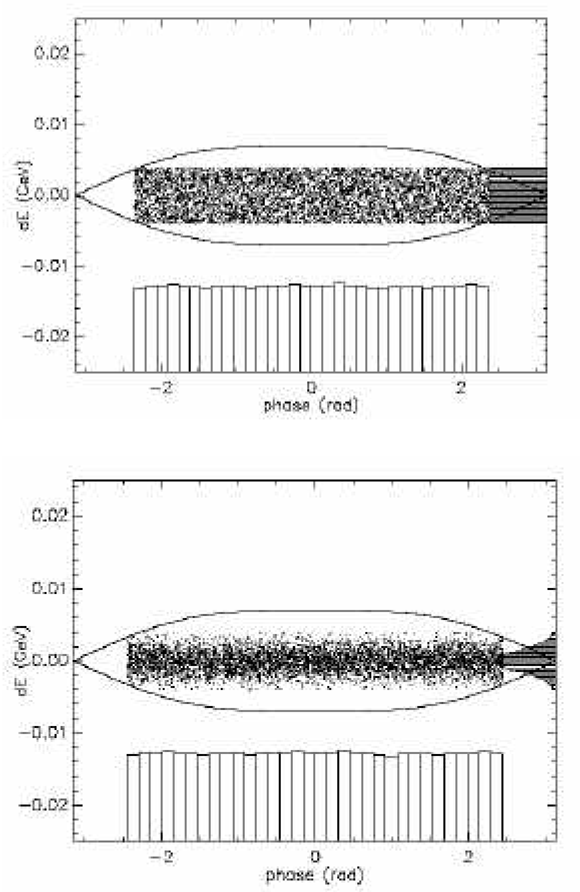
This case is similar to “case 3” above, but uses a single harmonic rather than a double harmonic RF. Phase plots at various times for this case are shown in Fig. 5. A 26% injection gap possible over most of the injection period, while still recouping the 250 ns extraction gap. This is a slightly larger chopped gap than possible with the corresponding dual harmonic case 3. In this case, the injection gap needs to be ramped to 40% slightly sooner than in case 3 (starting at turn 958, rather than 1058). The resultant beam at extraction has a 33% lower bunch factor than its dual harmonic counterpart, which may be troublesome with respect to transverse space charge effects. On the other hand the RMS energy spread is higher than the dual harmonic case. Also, a longer “spin cycle” is required for the $10^{-4}$ gap to reach a length of 250 ns, compared to the dual harmonic cases (see Fig. 4). Although not indicated in Fig. 4, allowing the beam to spin 160 turns after injection results in the $10^{-4}$ gap reaching a maximum extent of 300 ns.

*Case 6: single harmonic, 60 kV RF*

This final example is similar to the above case, except the RF voltage is allowed to increase to 60 kV. As with the dual harmonic case, using a 60 kV RF system a scenario is found with a 20% chopper gap over most of the injection while still achieving a 250 ns gap at extraction. This case has the smallest bunch factor and largest energy spread of the extracted beam of any cases examined here.

**Impact of longer storage time on transverse dynamics**

The alternate longitudinal injection scenarios described above call for storing the accumulated beam some additional “spin turns”, after particle injection is finished. The number of spin turns ranges from 10 to 70, corresponding to an additional 1 to 6% increase in the total number of turns. Here the impact on the growth of the accumulated beam transverse beam size due to space charge forces during the additional storage times is investigated. The ORBIT code is used, incorporating both longitudinal and transverse tracking, with space charge. A typical transverse correlated painting scheme is used, which minimizes the halo production and produces a relatively flat transverse profile. One million particles are tracked. The longitudinal scenario of case two above is employed. Figure 6 shows the percentage of particles above a given transverse emittance at the end of injection and also after additional spin turns. There is minimal growth in the transverse beam size with up to 100 additional spin turns beyond the particle injection.




a) Uniform ± 4 MeV input energy distribution

b) Gaussian distribution with $\sigma_E$ = 1.5 MeV, truncated at ± 4 MeV.

Figure 4. Different energy distributions, with dual harmonic RF initially at 10 kV, -5 kV.

**Summary**

Longitudinal injection scenarios are found with chopped gaps as low as 20% over most of the injection period, that meet the extraction gap criteria of 250 ns. These scenarios utilize a ramped RF voltage throughout injection, increase the chopped gap length over the last ~ 15% of injection, and allow a few additional tens of spin turns after particle injection. Reduced chopper gap cases are found where the bunch factors and RMS energy spread of accumulated beam are similar to the nominal scenario. Increasing the RF voltage from the present design value of 40 kV to 60 kV does not offer much benefit in further reducing the chopper gap. Use of a single harmonic RF results in a similar minimum chopped gap length, but the resulting accumulated beam has a bunch factor

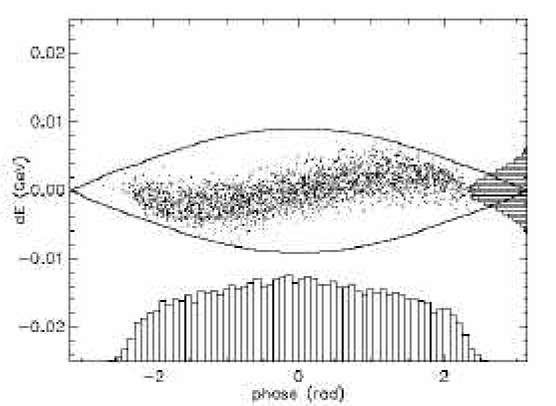
~one third lower than the dual harmonic cases. Use of a more peaked truncated gaussian energy distribution of the injected beam (compared to the nominal uniform distribution) permits a reduction of ~ 10% in the chopped gap length, and results in an accumulated beam with a similar RMS energy spread. Use of a few tens of additional spin turns after injection, to allow the longitudinal gap to clear up, leads to only a few percent increase in the transverse emittance profile due to space charge.

**References**


1. ORBIT User Manual, http://www.ornl.gov/sns/APGroup/Codes/ORBITUserMan1_10.html

2. E. Lessner, ANL, private communication, Sept. 1999.

3. IPNS Upgrade A Feasibility Study, ANL-95/13, April 1995.



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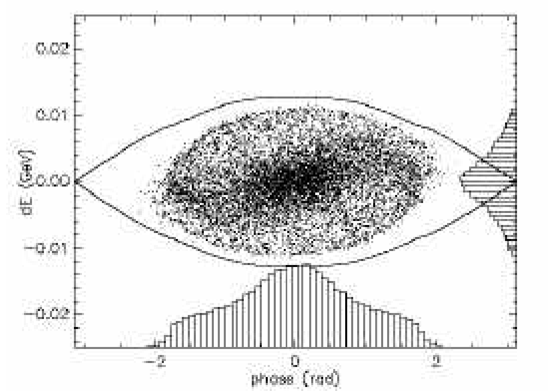
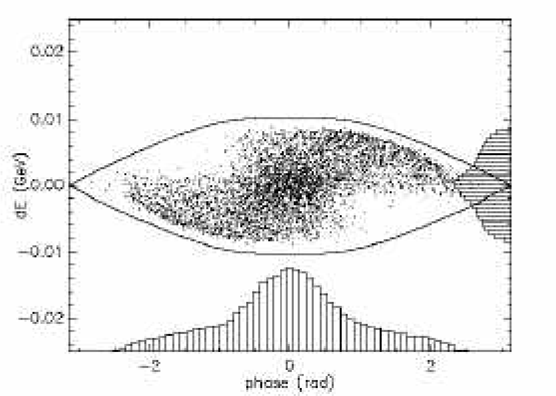


Turn 1158 (end of injection)



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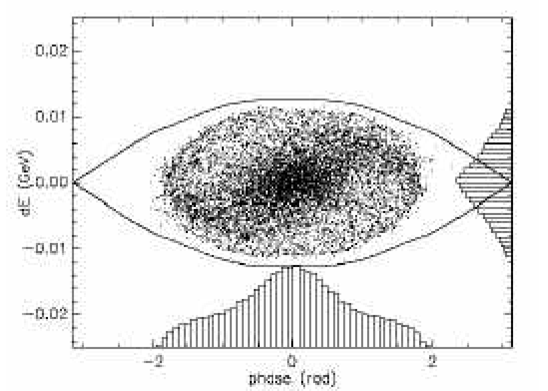
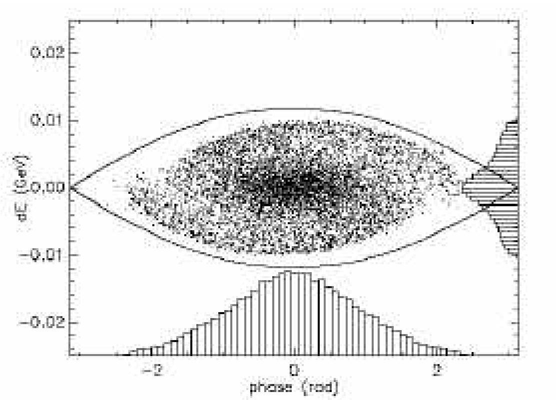
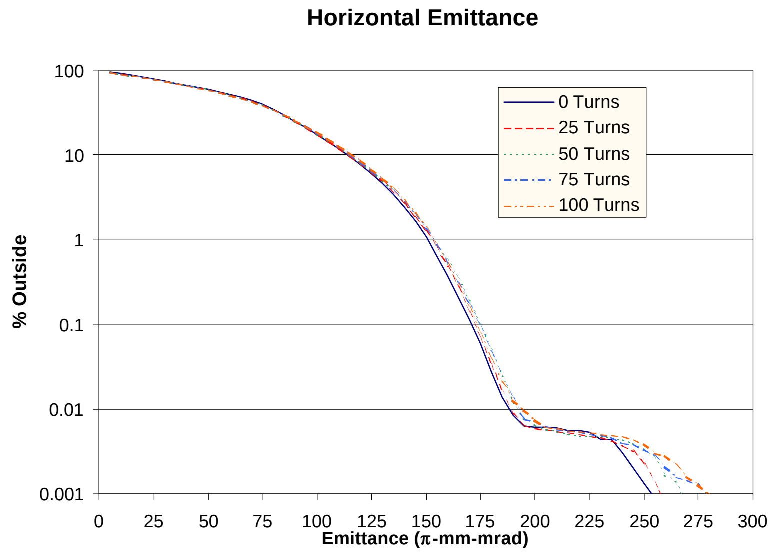


Turn 1228 (extraction)



Turn 900

Figure 5. Phase space plots during the beam accumulation period for an adiabatic capture injection scenario, using 40 kV single harmonic RF.



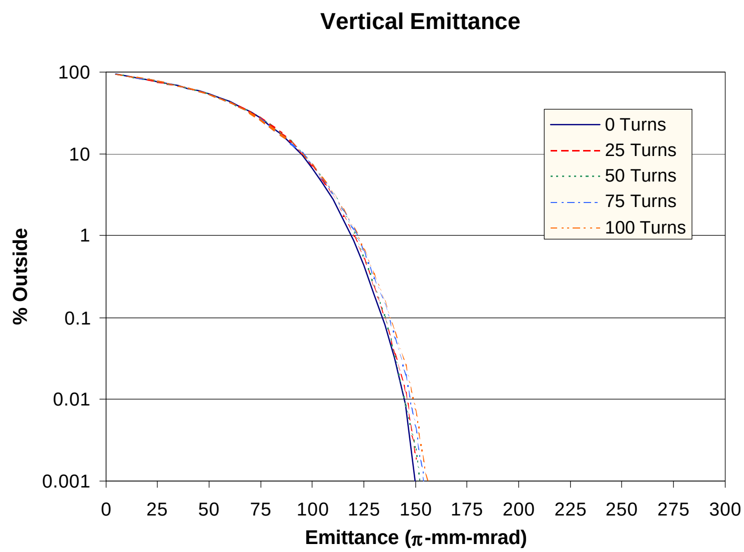




Figure 6. Percentage of particles beyond a given transverse emittance, for different numbers of additional storage spin turns, beyond the injection period.