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The Modeling of RF Stacking of Protons in the Accumulator[1]

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1. Introduction

When the Run2 collider program is terminated in 2009, the present pbar source will be available for other usages. One possible application is to convert the Antiproton Accumulator to a proton accumulator so that the beam power from the Main Injector could be greatly enhanced [1]. The Accumulator has the unique feature of very large momentum acceptance. It is possible to stack 3 – 4 Booster batches in the longitudinal phase space before transferring them to the Main Injector or Recycler. This note shows the simulation of RF stacking using the code ESME [2].

2. Simulation parameters

Table 1 lists the parameters. The lattice of the Accumulator is the one at injection [3].

Table 1. Parameters

Particle	Proton
Circumference (m)	474.1
Mean radius (m)	75.47
Kinetic energy (GeV)	8.0
Total energy (GeV)	8.938
Momentum (GeV/c)	8.889
Transition γ	5.421730
Transition energy (GeV)	5.0871
Momentum compaction factor α	0.034
Slip factor η	0.023
Relativistic β	0.9945
Relativistic γ	9.5263
Revolution time τ_0 (μs)	1.59
Injected beam intensity (protons per bunch)	4×10^{10}
Number of bunches	84
Injected beam intensity (protons per batch)	3.4×10^{12}
Number of stacked batches	3 ~ 4
Total beam intensity after stacking	$1.02 \sim 1.36 \times 10^{13}$
Injected beam emittance (per bunch, eV-s)	0.1
Emittance after stacking (per bunch, eV-s)	≤ 0.5
Longitudinal bunch profile	Elliptical
RF frequency (MHz)	53
Harmonic number	84
Peak RF voltage (kV)	250
Synchrotron tune	3×10^{-3}
Synchrotron period (ms)	0.539
Stationary bucket area (eV-s)	0.65
Stationary bucket height (MeV)	27
Deceleration synchronous phase ϕ_s	$-3°$
Deceleration time (ms)	30

3. RF stacking procedure

The simulation uses 1000 macro-particles for each injected proton bunch (53 MHz). The longitudinal beam profile is elliptical. Space charge effect is included. The procedure is as follows:

1) Injection of the first batch:
   a. Synchronous injection:
      A batch of 84 proton bunches from the Booster are injected into the stationary 53 MHz 250 kV RF bucket in the Accumulator and captured. *(Figure 1)*

   b. Bucket transformation:
      Transform the stationary RF bucket to a moving bucket by altering synchronous phase (ϕ_s) slowly (for about 0.1 ms) from 0° to –3°. *(Figure 2)*

   c. Deceleration:
      At a synchronous phase of –3°and RF voltage of 250 kV, the beam is slowly decelerated by 150 MeV. It takes about 30 ms. *(Figure 3)*

   d. Adiabatic debunching:
      Near the end of deceleration, the synchronous phase is reduced to zero. The RF voltage is then adiabatically decreased from 250 kV to zero and the beam is debunched. This stage takes about another 30 ms. *(Figure 4)*

   The whole process takes about 60 ms and can be done at 15 Hz. The RF voltage and synchronous phase waveforms can be found in Figures 17 and 18, respectively.

2) Injection of the second batch:
   The above process is repeated with the exception that the deceleration is now reduced to about 143 MeV. The second batch should be brought as near as possible to the first one without perturbing it considerably. This requires laborious attempts to optimize the deceleration RF waveform. *(Figures 5-7)*

3) Injection of the third and fourth batches:
   Similar to 2) but with even smaller amount of deceleration. *(Figures 8-12)*

4) Adiabatic rebunching and acceleration:
   After the stacking is completed, the 53 MHz RF is slowly turned on with RF phase 0˚ to adiabatically recapture the beam. Then the bucket is slowly transformed from stationary to a moving bucket and the beam is gradually accelerated and brought back to the injection orbit so that it can be extracted. This process takes about 60 ms.

5) Extraction:
   The stacked high intensity beam is then extracted from the Accumulator and injected to the Main Injector or Recycler (depending on different assumption of operation scenarios, see [1]).

4. Simulation results

The longitudinal phase space plots at different stages of this process are shown in figures 1-12. In addition, a "movie" has also been made and can be found on the web [4]. The horizontal axis in these plots is in unit of degrees, with the machine circumference assumed to be 360°.

Figure 13 is the azimuthal distribution of 4 stacked batches after debunching. It is close to uniform. However, the energy distribution in Figure 14 shows gaps between successive batches. These gaps are inevitable in order to minimize the effects of the moving buckets on the circulating dc beams during deceleration. Stack tails are also visible in the case of stacking 4 batches. (It is much smaller when only 3 batches are stacked.)

Figure 15 shows the recaptured 3-stack beam. The emittance is well within the 0.5 eV-s bucket, which is equal to the Main Injector acceptance (see below). Figure 16 is the recaptured 4-stack beam. It fills the 0.5 eV-s bucket with some particles outside the bucket due to the high momentum stack tails in Figure 14.

5. Discussion

One main concern of RF stacking is the emittance dilution. The formation of "stack tail" can be clearly seen in Figure 14. It is caused by the approaching RF bucket on the existing circulating beam during the 2nd, 3rd and 4th injection, which is usually called *phase displacement acceleration* of dc beams. This tail is much smaller when only 3 batches are stacked, because the energy gap between neighboring batches is less tight. There is a trade-off between higher longitudinal beam intensity and smaller stack tail.

The stack tail must be dumped before it would enter the Main Injector. One way to get rid of it is to have a momentum collimator in the beam transport line.

The emittance of the stacked beam must be within the acceptance of the Main Injector, which was measured at about 0.7 eV-s when the batch intensity was 8.7×10^{12}. The acceptance would be smaller at higher intensities. So the allowable emittance after stacking is set to be 0.5 eV-s. This requirement can be met in 3-batch stacking but is more difficult if 4 batches need to be stacked.

The injection kicker has a mechanical shutter, which is unable to move at 15 Hz. Fortunately, the effective range of the kicker field is small and has no effect on the circulating beam when fired even without the shutter.

Acknowledgements

One of the authors (Phil Yoon) is grateful to J. MacLachlan for helpful discussions and advice on RF stacking simulations, and reviewing this document.

References

[1] D. McGinnis, to be published.
[2] J. A. MacLachlan, *Multiparticle dynamics in the E-ϕ tracking code ESME*, Fermilab-Conf-02/102
[3] http://lattices.fnal.gov
[4] http://www-ap.fnal.gov/~syoon/Accum.html
(An animated RF-stacking process is available)

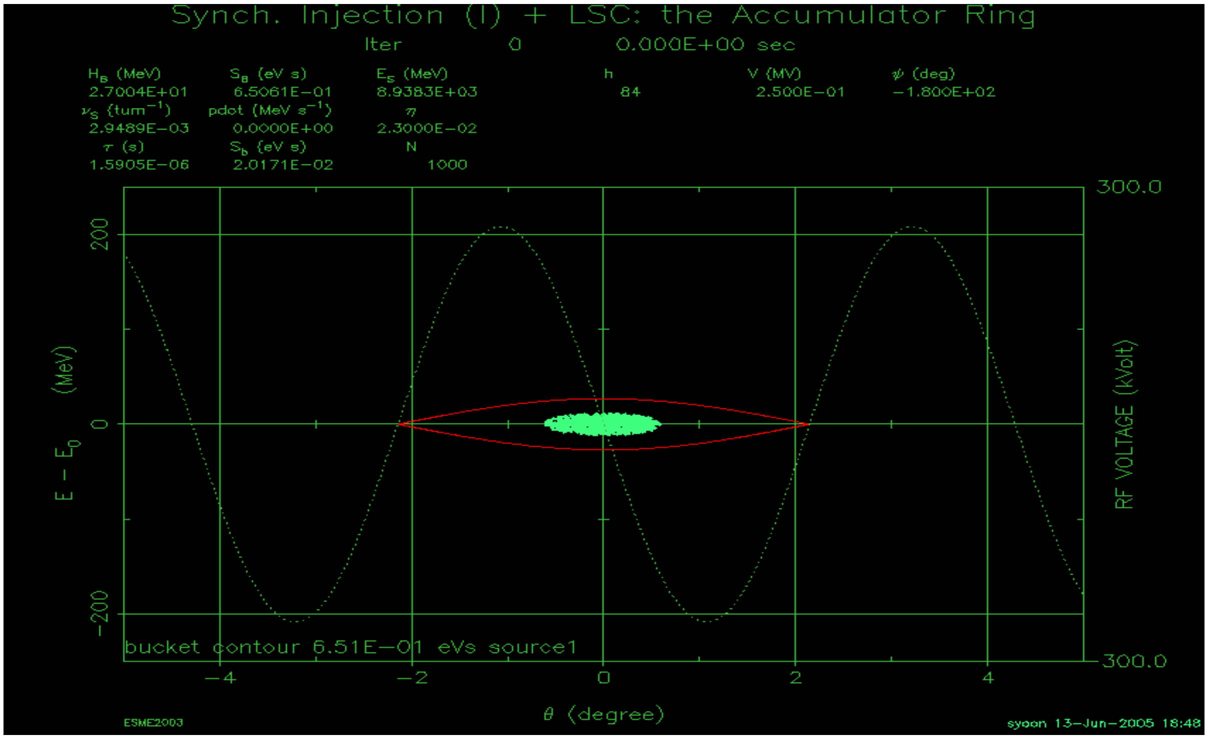

Figure 1. First synchronous injection

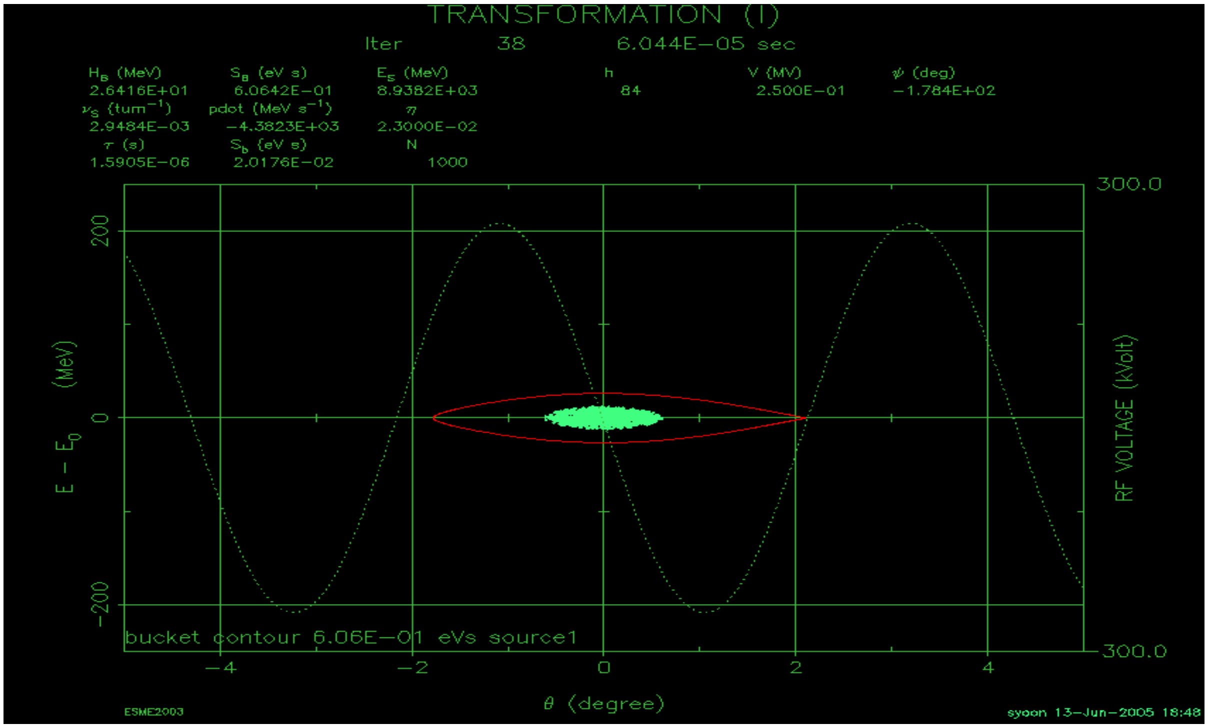

Figure 2. Adiabatic transformation from a stationary RF bucket to a moving RF bucket

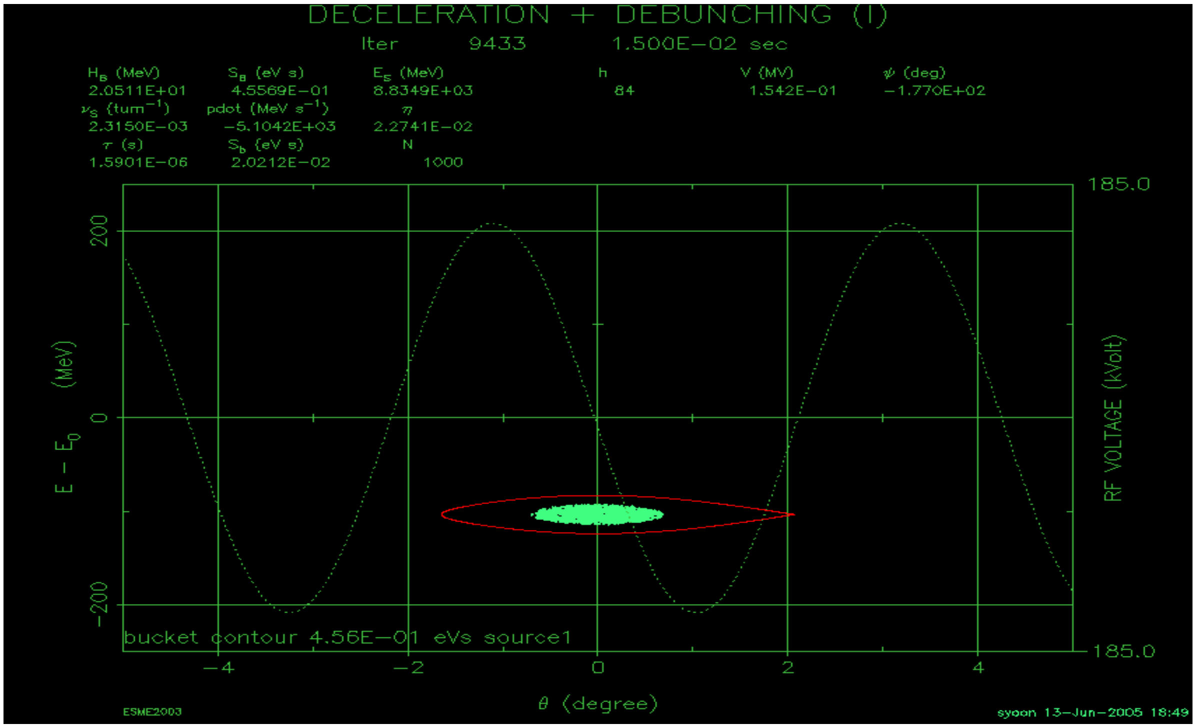

Figure 3. Deceleration and adiabatic debunching process (First batch)

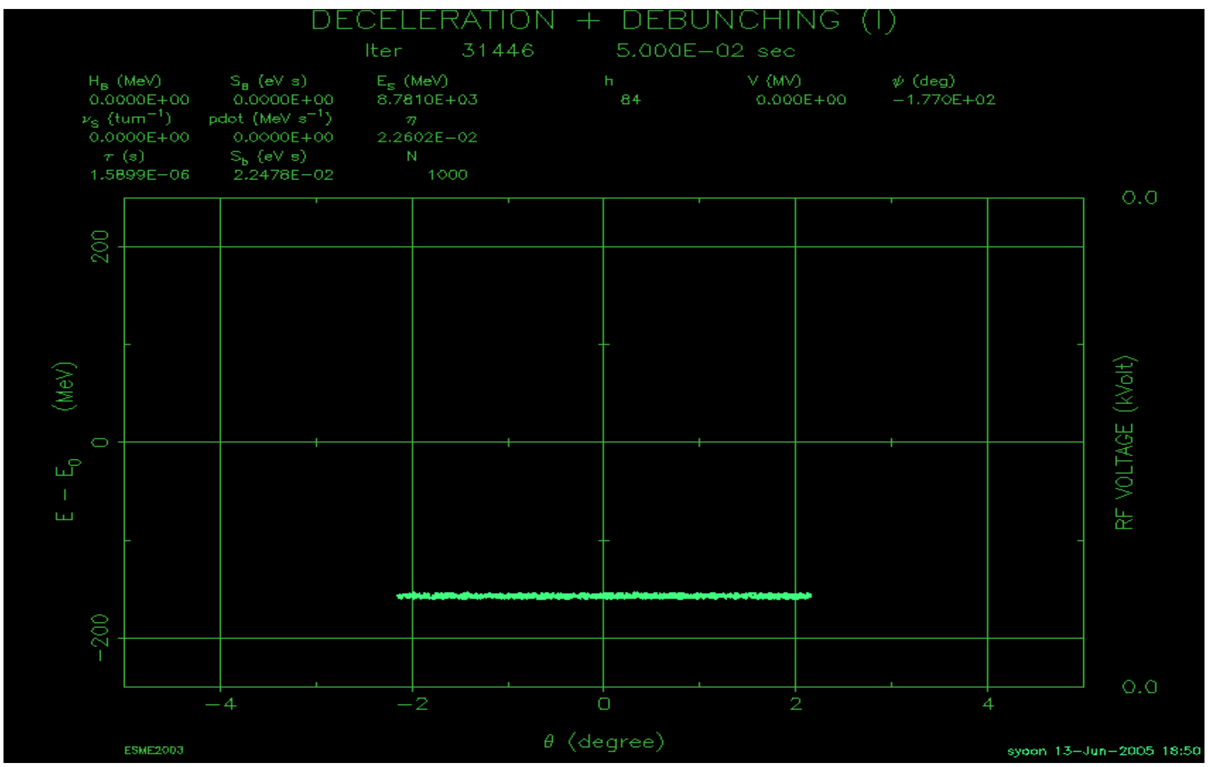

Figure 4. Debunched beam (First batch)

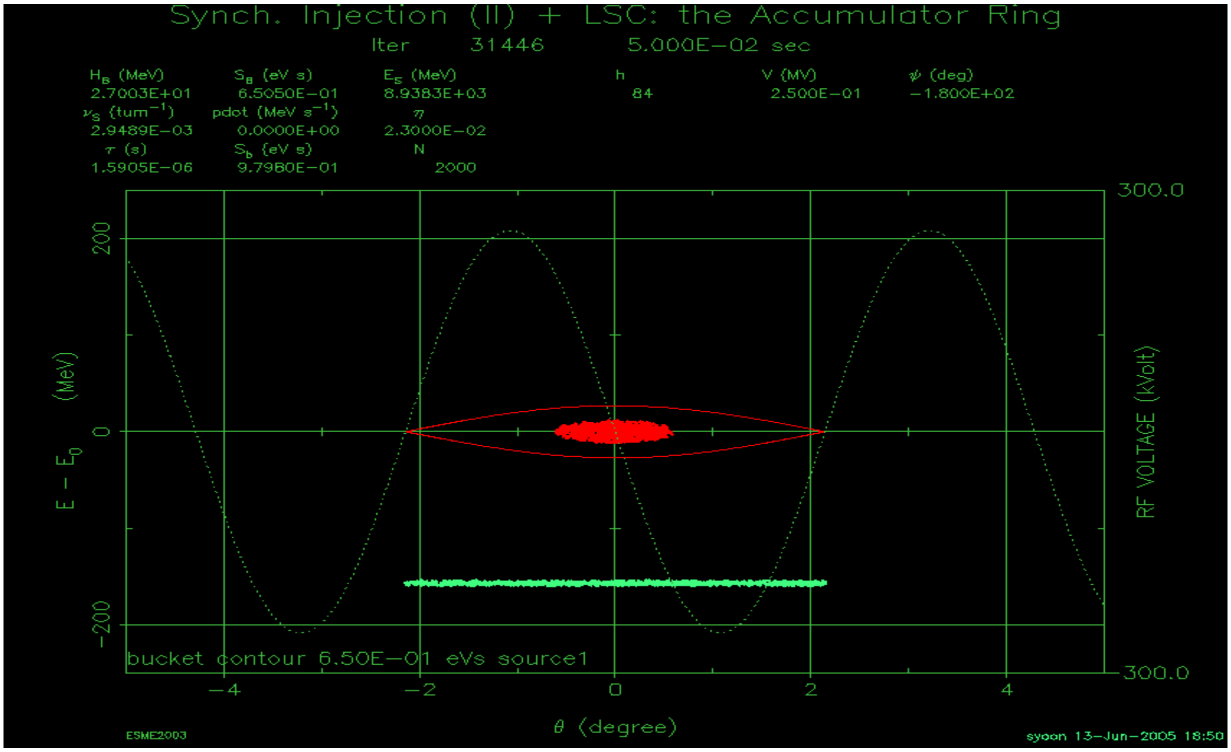

Figure 5. Second injection

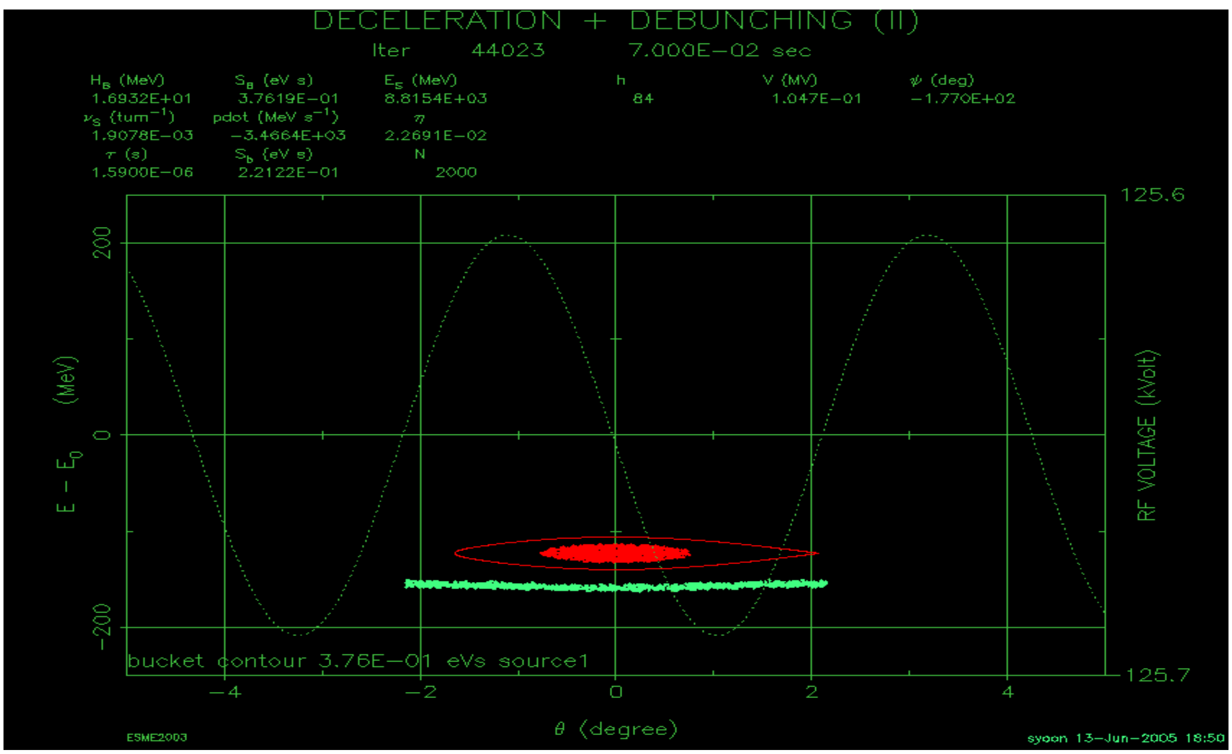

Figure 6. Deceleration and debunching procress (Second batch)

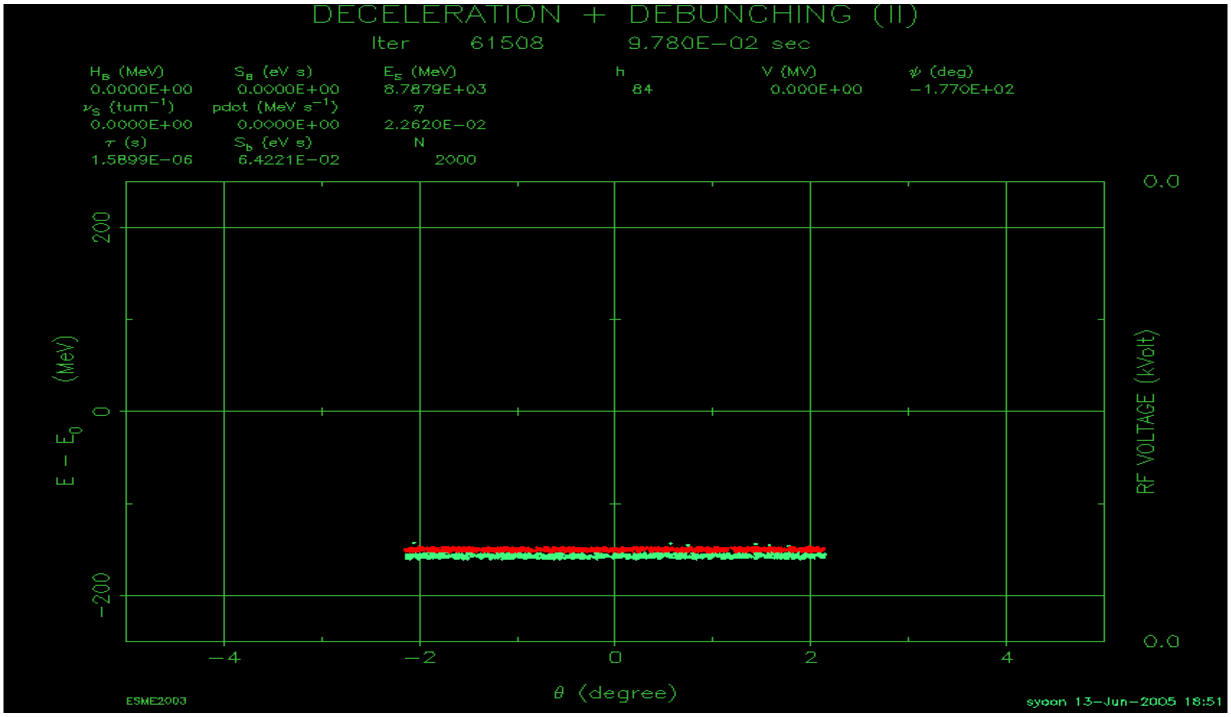

Figure 7. Stacking of 2 batches

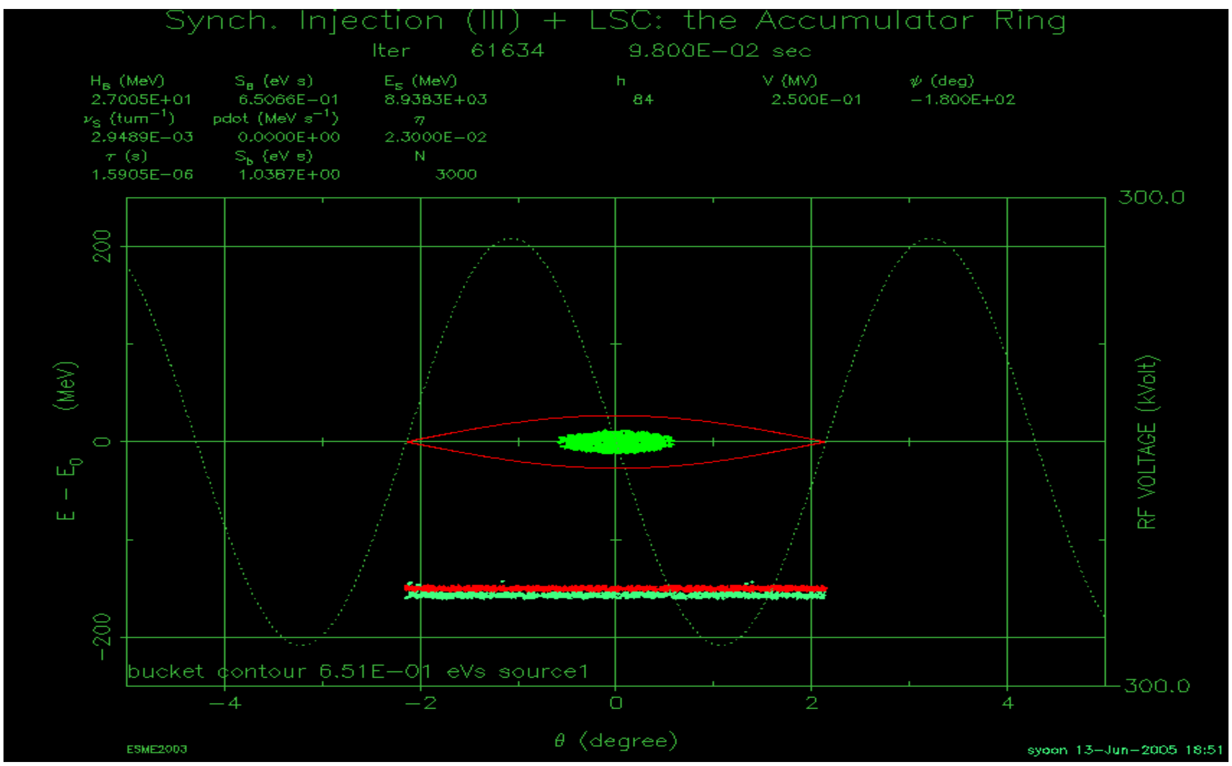

Figure 8. Third injection

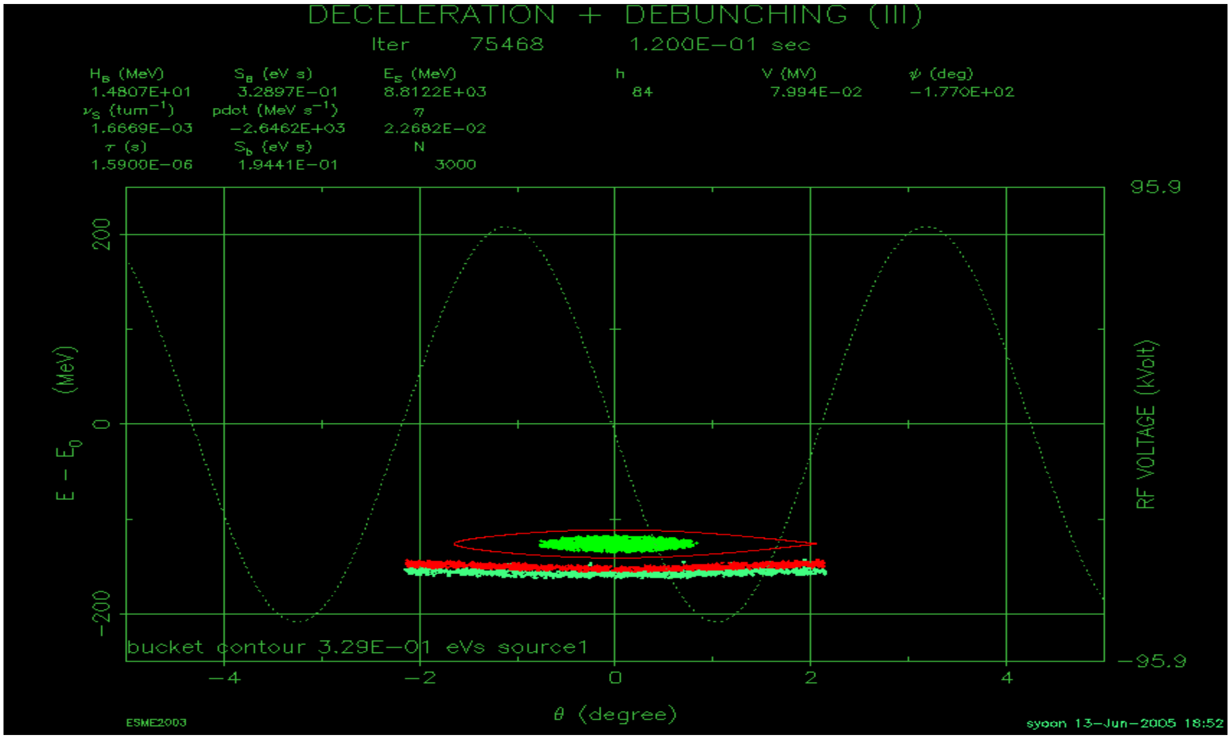

Figure 9. Deceleration and debunching process (third batch)

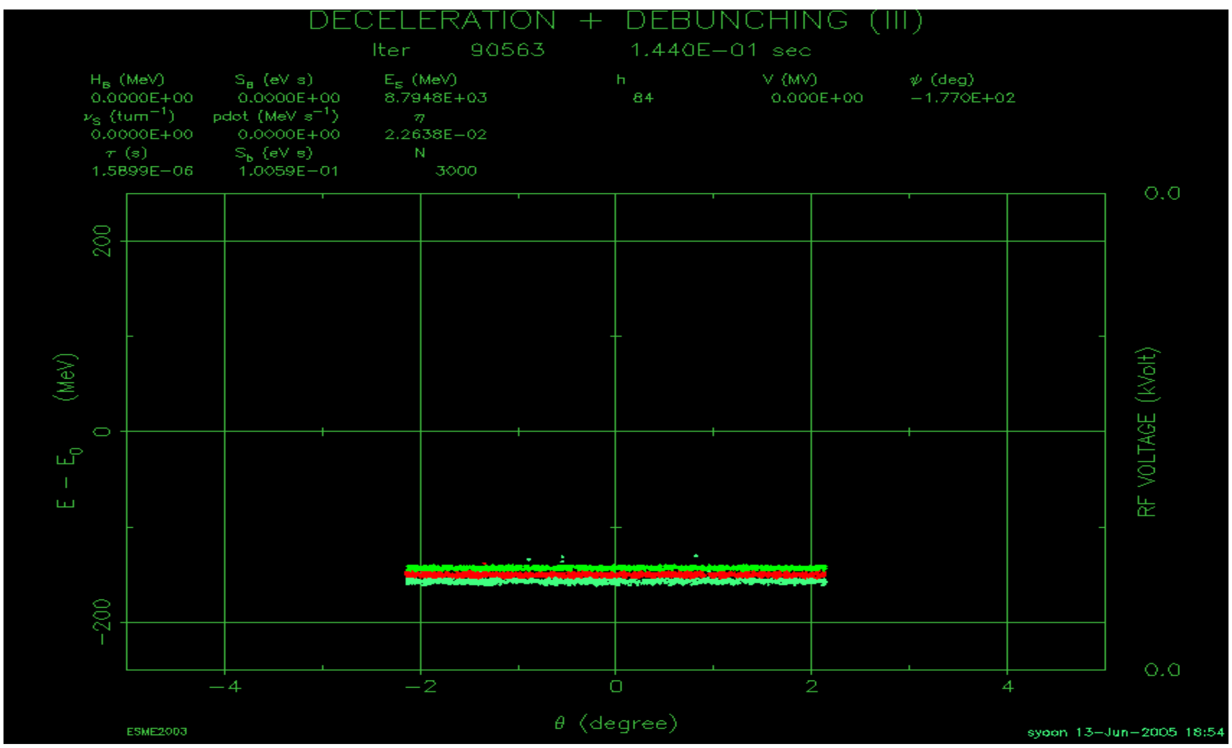

Figure 10. Stacking of 3 batches

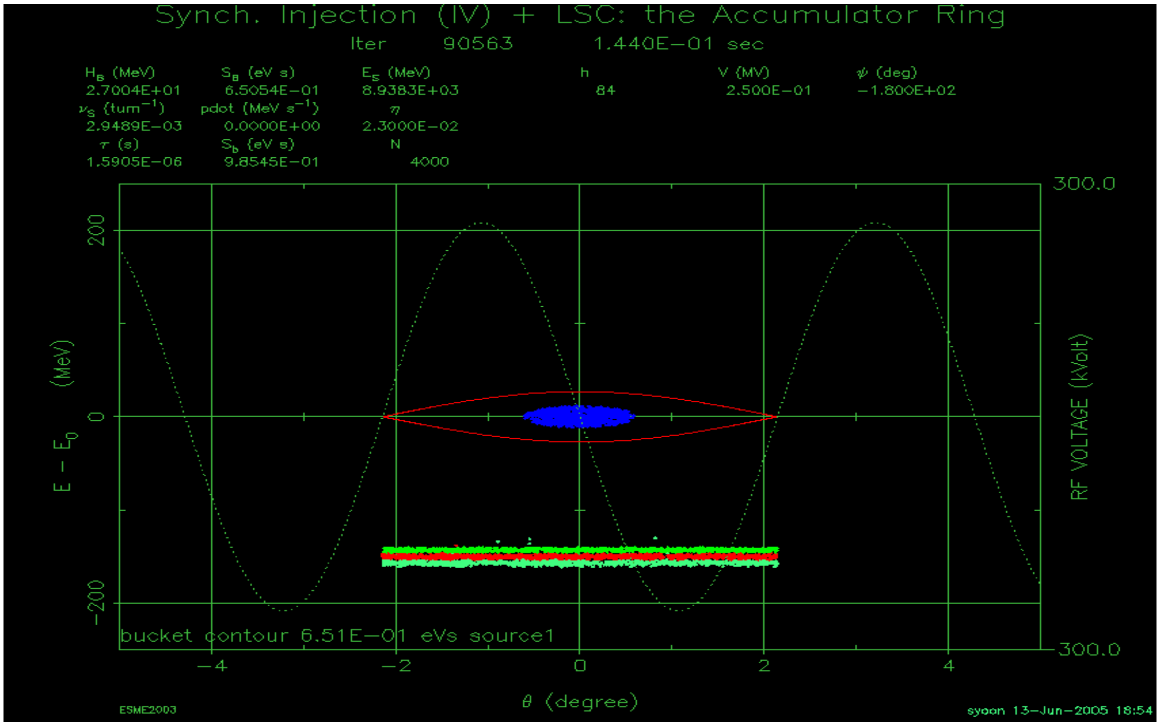

Figure 11. Fourth injection

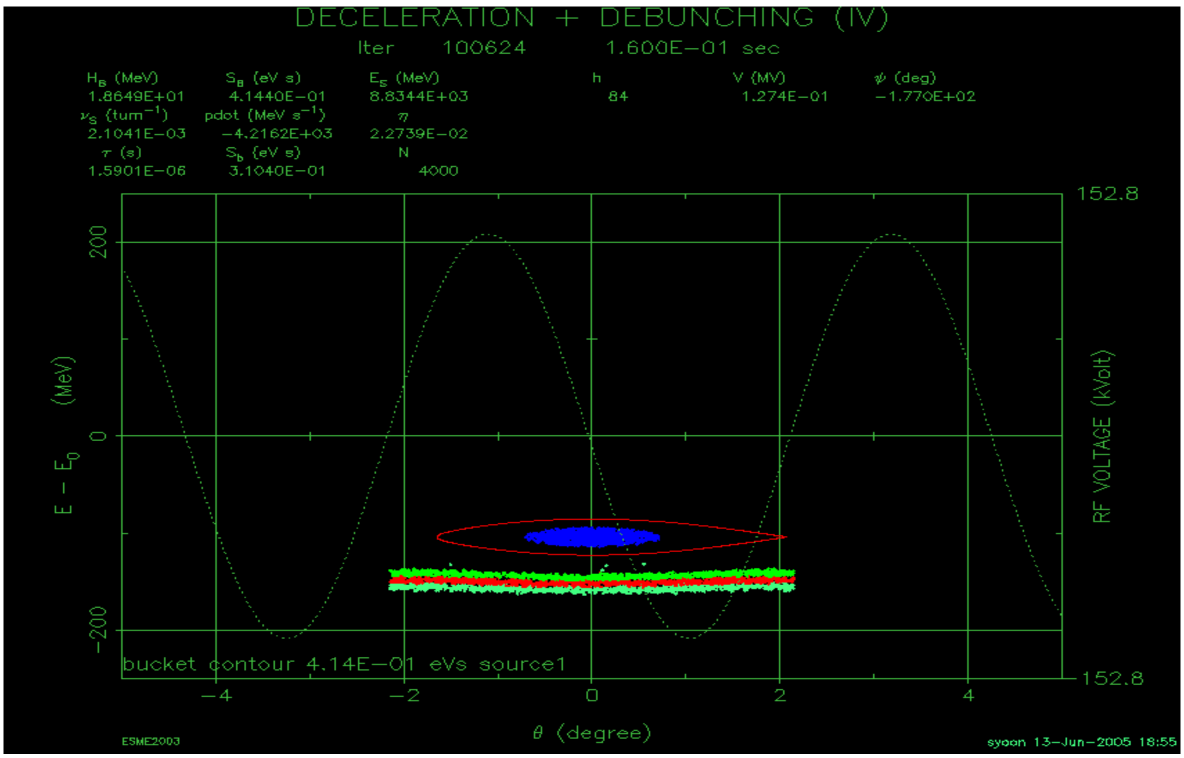

Figure 12. Deceleration and debunching process (fourth batch)

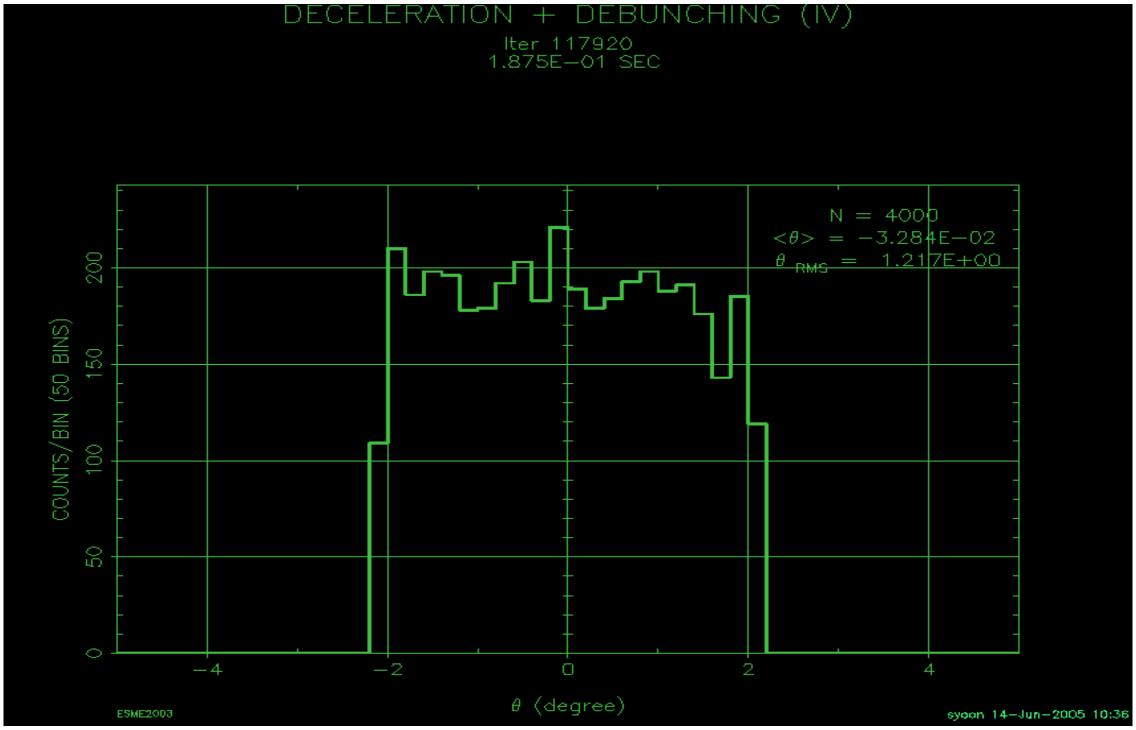

Figure 13. Azimuthal distribution with 4 stacked batches

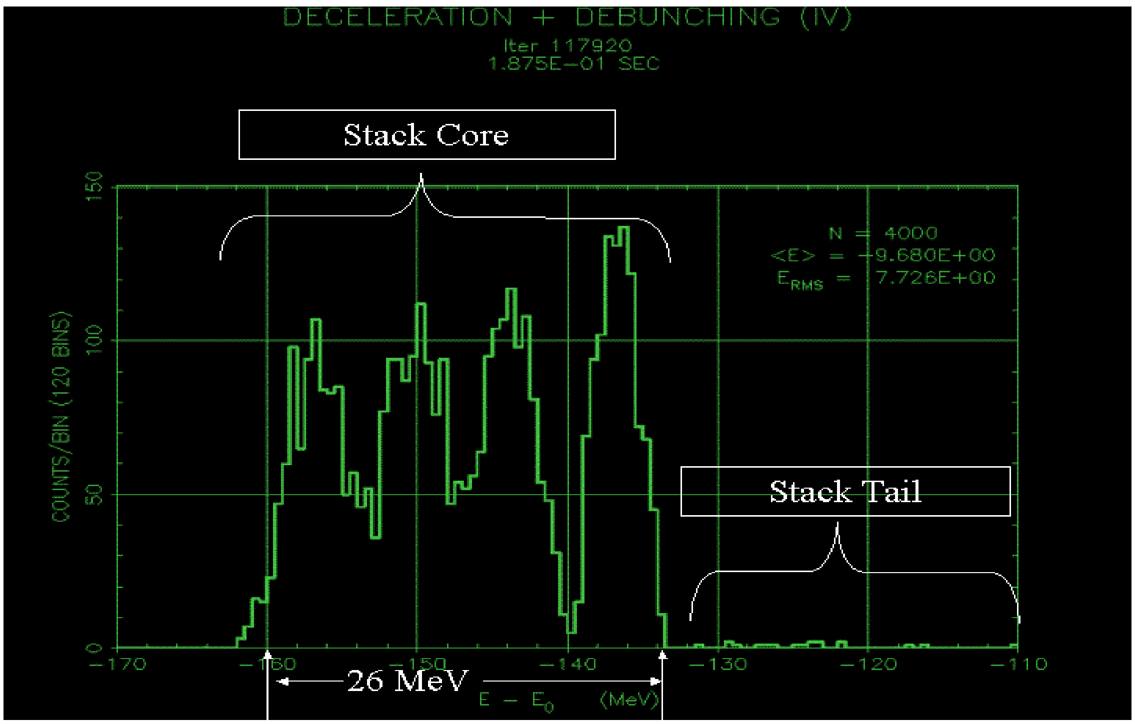

Figure 14. Energy distribution; Stack core and stack tail after stacking of 4 batches.

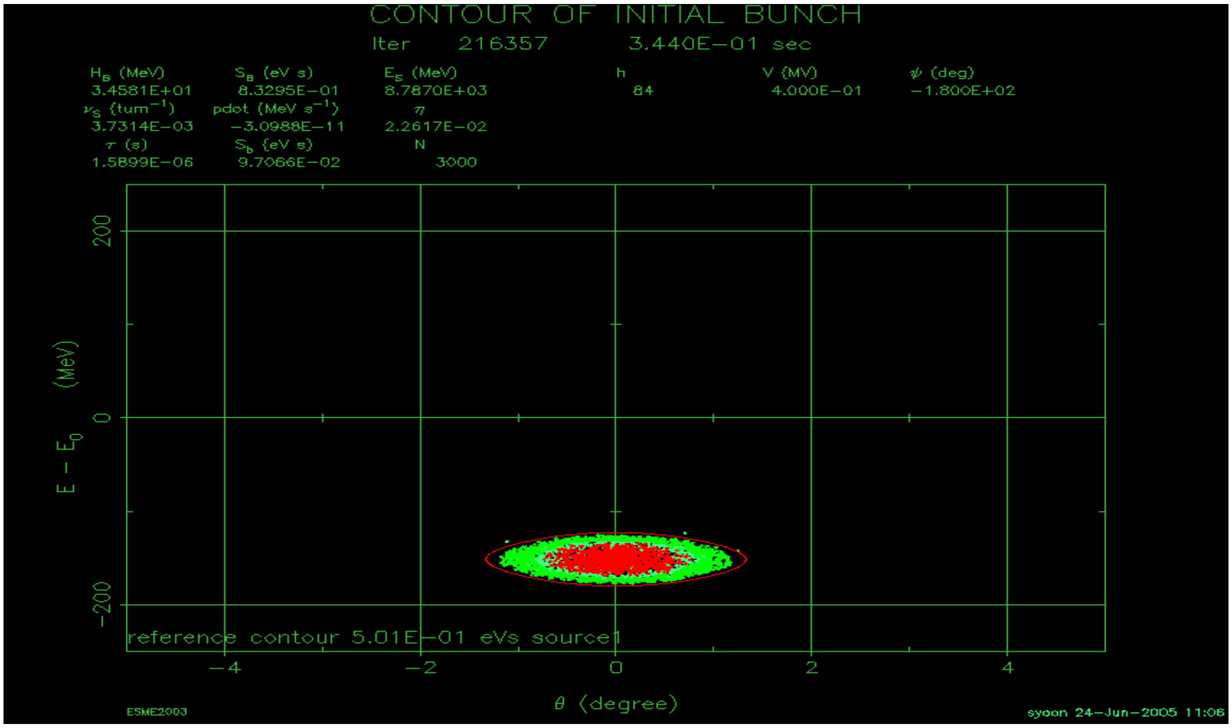

Figure 15. Adiabatic recapture of 3 stacked batches.
(reference bucket contour of 0.5 eV-s is drawn.)

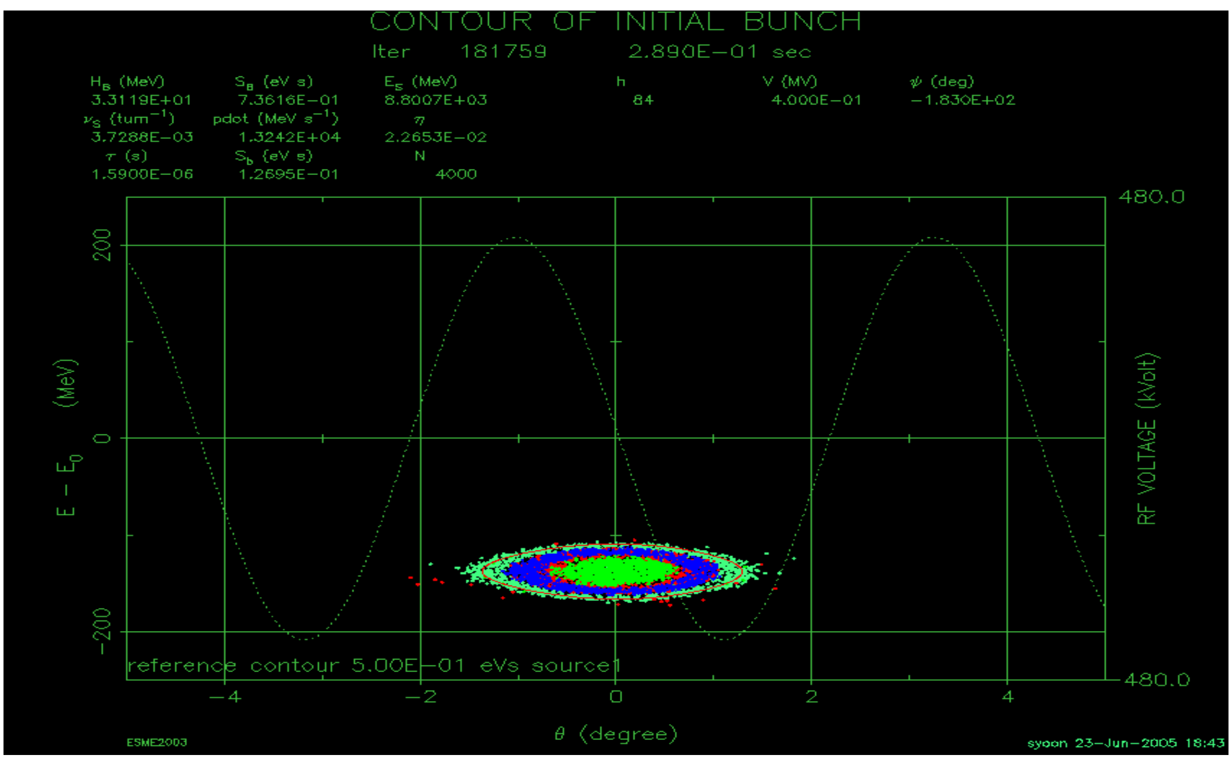

Figure 16. Adiabatic recapture of 4 stacked batches
(reference bucket contour of 0.5 eV-s is drawn)

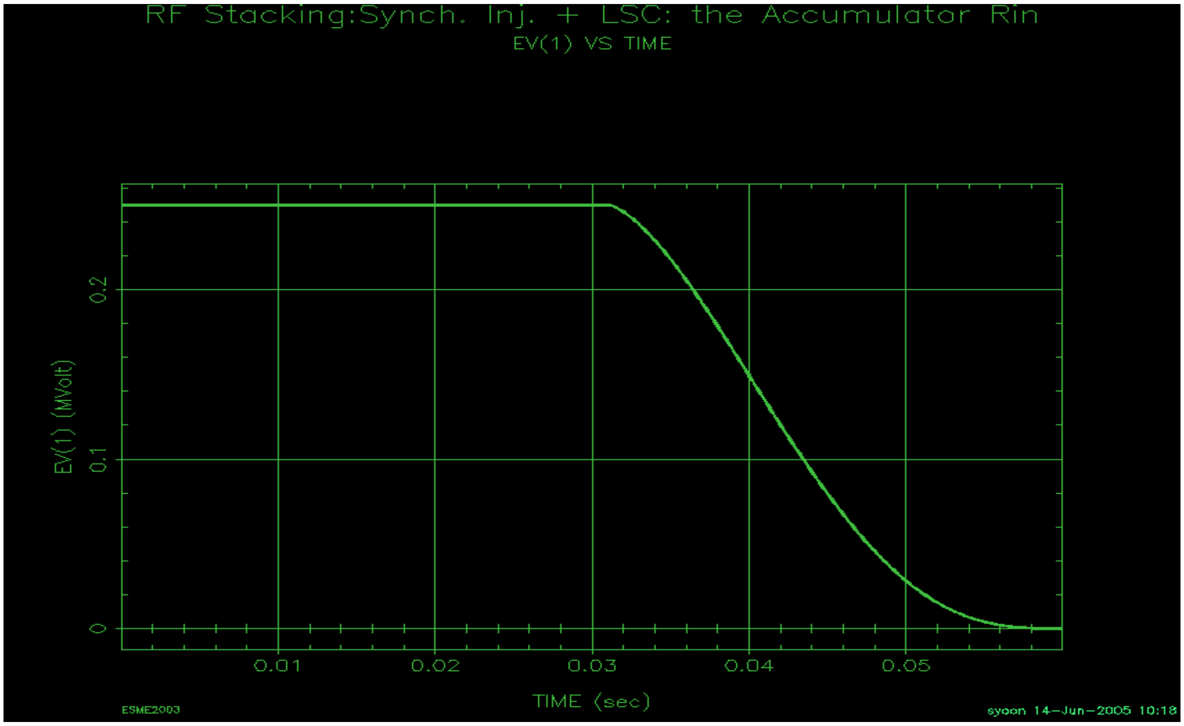

Figure 17. RF voltage waveform during one cycle of RF stacking

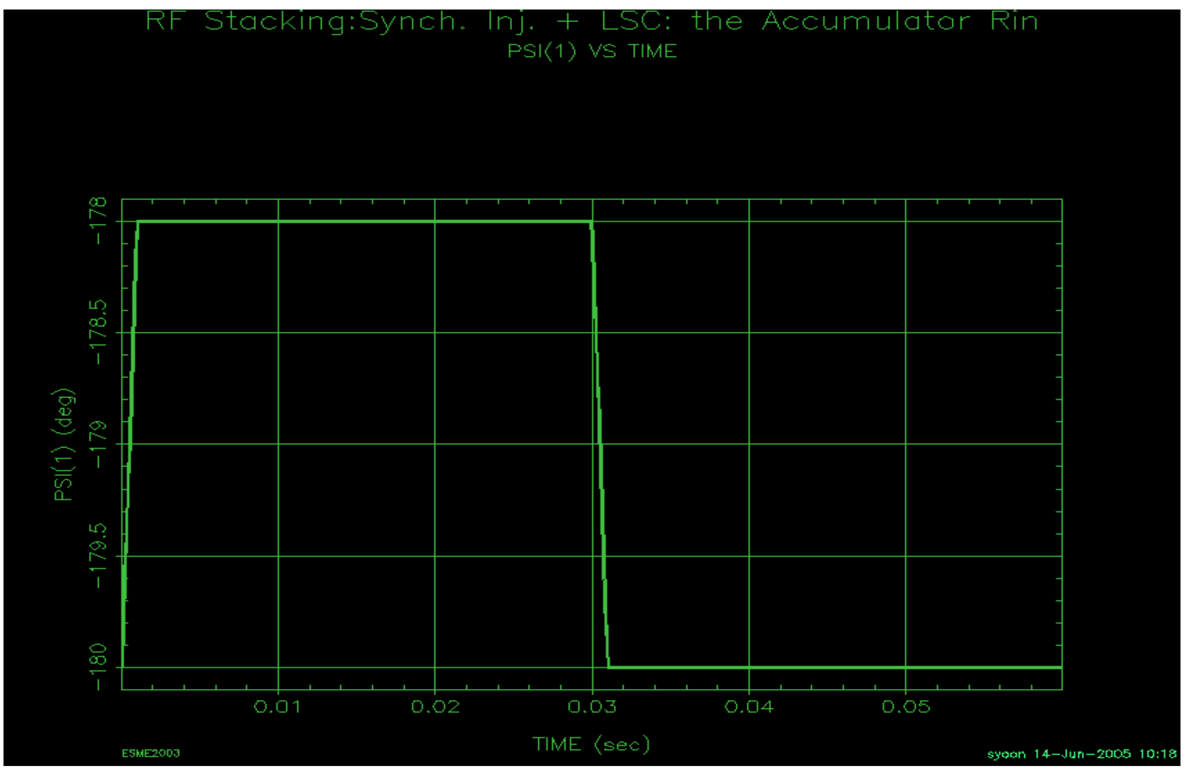

Figure 18. RF phase waveform during one cycle of RF stacking