Simulation of Main Injector 2.5 MHz Pbar Acceleration with Space Charge and Beam Loading Effects

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In Run II four pbar bunches from the Recycler will be accelerated in the Main Injector from 8 GeV to 150 GeV. At 150 GeV the pbar bunches will be injected into the Tevatron for collider operation. Pbar transfer from Recycler to Main Injector is envisioned as 2.5 MHz bucket to bucket transfer. An acceleration scheme with a slow ramp (2.5 MHz acceleration) followed by a fast ramp (53 MHz acceleration) was previously developed. (See references [1, 2, 3].) The simulations in this report follow a similar track as those of [1, 2, 3] with the inclusions of space charge, beam loading and other miscellaneous effects. The simulations are performed using the ESME program [4].

The initial beam and rf parameters in the following table are obtained from the Recycler Ring Technical Design Report.

- Total beam energy (GeV): 8.938
- Momentum compaction factor: -0.008683
- Rf frequency (MHz): 2.5
- Rf voltage for 2.5 MHz rf system (kV): 2
- Invariant 95% longitudinal emittance (eVs): 1.5 / per bunch
- Number of particles per bunch: 6E10

The 2.5 MHz pbar acceleration scheme is first simulated without space charge and beam loading. The ramp and dp/dt are shown in figures 1-3.

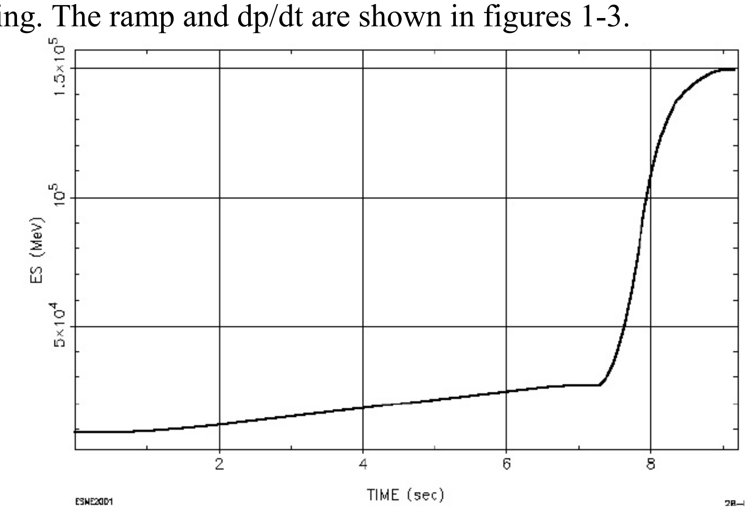


Fig. 1 Energy curve for the entire cycle.

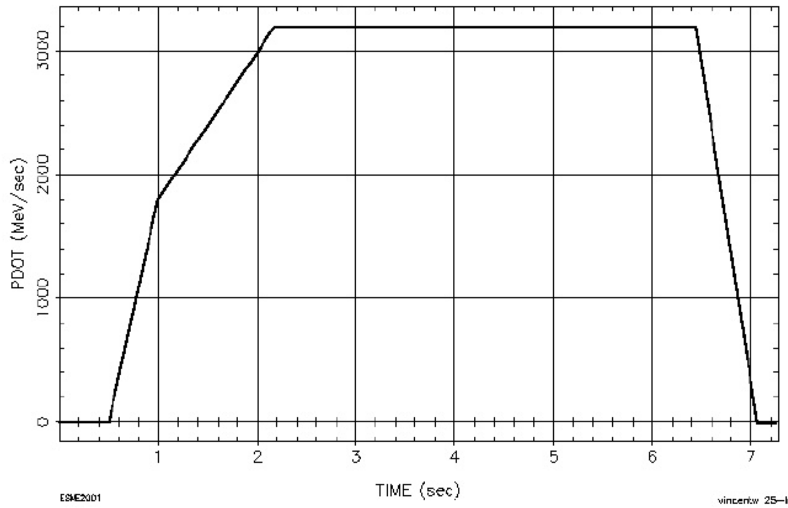


Fig. 2 dP/dt for the 2.5 MHz acceleration (first 7.3 seconds of the ramp).

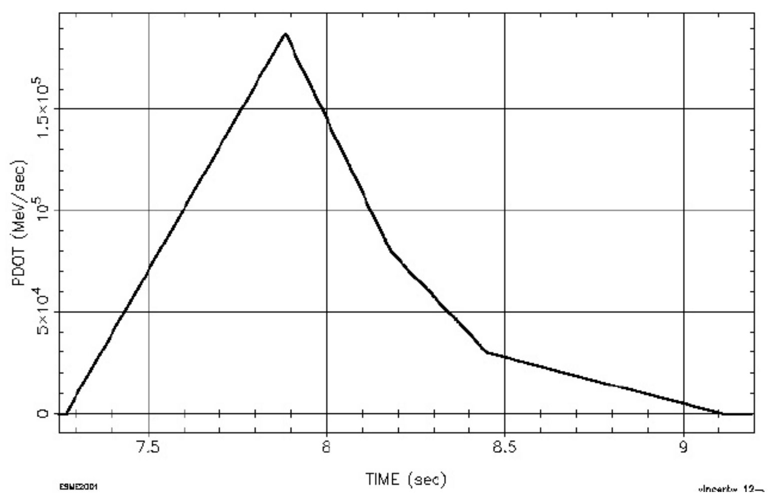


Fig. 3 dP/dt for the 53 MHz acceleration (last 2 seconds of the ramp).

The voltage and rf phase are shown in figures 4-7. The acceleration cycle begins with an adiabatic shrink of the bunch at 8 GeV for 0.5 second. During this period of time, the rf voltage increases from 2 kV to 50 kV adiabatically. After the bunch shrinkage, the beam is accelerated to 27 GeV using the 2.5 MHz rf system in about 6.6 seconds. The 2.5 MHz acceleration voltage is shown in Fig. 5. Because of the lack of phase focusing at transition, the rf voltage is lowered in the region of transition to reduce the energy spread. Simulation shows that this maneuver eases the problem of emittance dilution due to transition crossing. The emittance (rms) dilution for crossing transition is about 2 %.

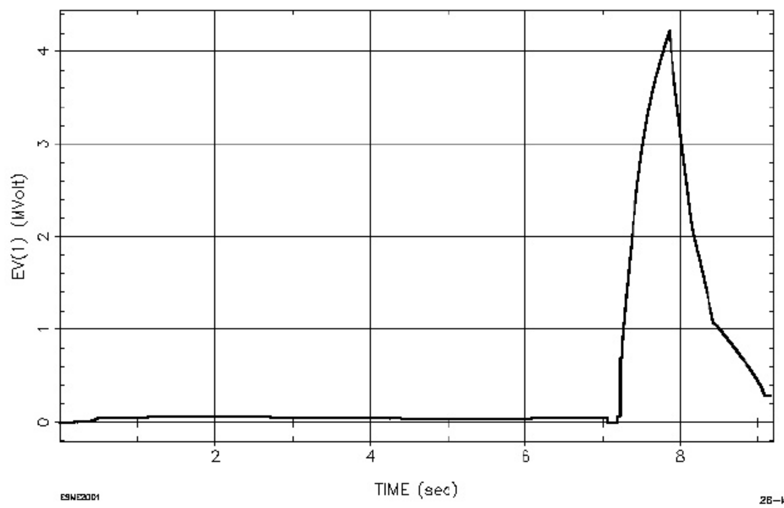


Fig. 4 Voltage program for the entire cycle.

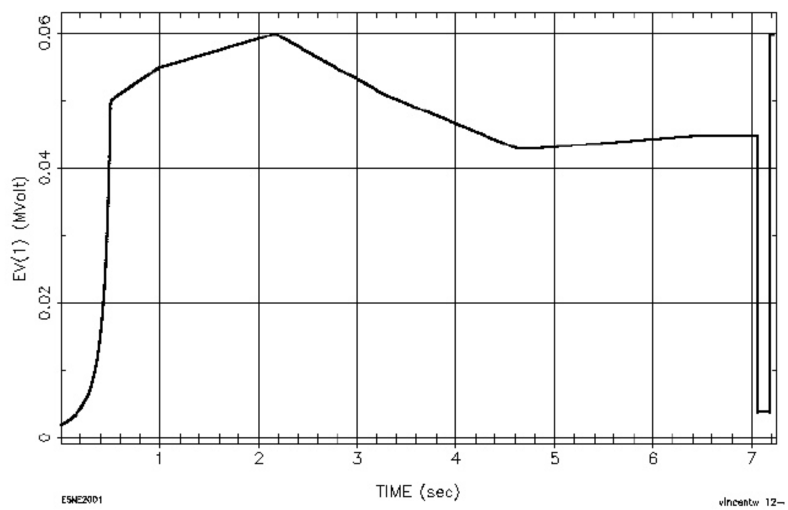


Fig. 5 The 2.5 MHz voltage program (first 7.3 seconds in figure 4). Transition occurs at about 4.7 second and at a energy of 20.49 GeV. The voltage at transition is 43 kV and the phase is 58 degree. See Fig. 6 for the rf phase.

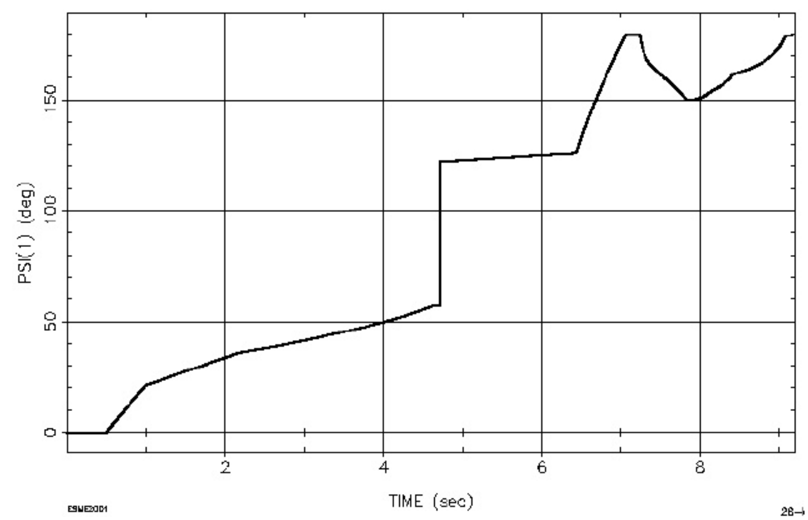


Fig. 6 Rf phase during the entire cycle.

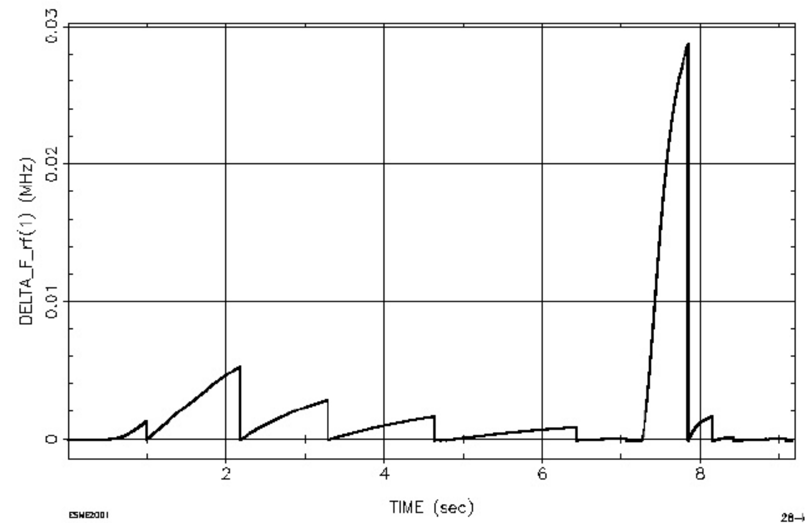


Fig. 7 Change in rf frequency during the entire cycle. For the first 7.1 seconds, the base frequency (at the beginning of the cycle) is 2.5136 MHz. The maximum frequency change for the 2.5 MHz acceleration is about 6 kHz. This is within the 25 kHz frequency range (bandwidth) of the 2.5 MHz cavity. For the last 2 seconds, the base (starting) frequency is 53.046 MHz. The maximum frequency change during the 53 MHz acceleration is about 29 kHz. This is within the tuning range of the cavity which is 52.8 MHz to 53.1 MHz.

At the 27 GeV front porch, the voltage snaps to 4 kV and the bunch undergoes a quarter period of synchrotron rotation to stretch out. Then the voltage is raised to 60 kV for a fast rotation. At minimum bunch width, the bunch is captured by the 53 MHz bucket with about 0.7 MV. The first rotation takes about 115 ms and the second rotation takes about 46 ms. After the capture, the 53 MHz bunch is accelerated to 150 GeV. The entire acceleration cycle is about 9.2 second. Figure 8 shows some bunch samples during the cycle.

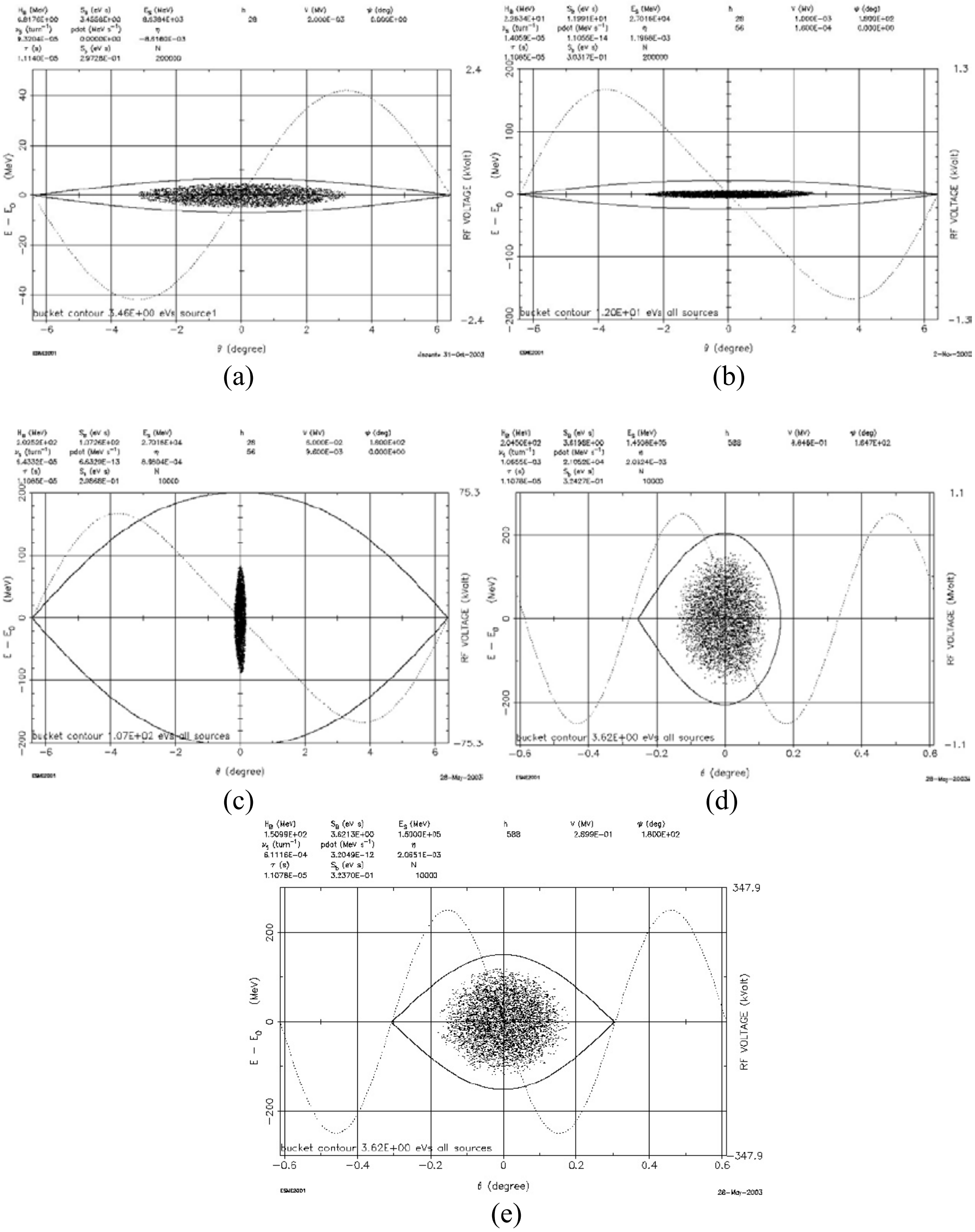


Fig. 8 (a) Initial beam at 8 GeV. (b) At 27 GeV front porch before rotation. (c) At the end of second rotation before 53 MHz capture. (d) 53 MHz acceleration. (e) Final beam at 150 GeV.

Plot (a) in Fig. 8 is the initial bunch with an emittance (95%) of 1.3 eVs. The second (b) and third (c) pictures are before the second rotation and at the end of the second rotation, respectively. The fourth (d) picture is an accelerating 53 MHz bunch and the last (e) picture is at 150 GeV flattop with a final emittance (95%) of about1.5 eVs. There is no particle loss during the cycle.

The antiproton bunch intensity is about a factor of 10 smaller than typical Main Injector operation. However, because of the unusually long (or slow) ramp, simulation with space charge is carried out to check emittance dilution. The effects of beam space charge and coupling impedance between the beam and the beam pipe are simulated with the following input parameters. (See reference 5 for the theoretical basis.)

- Assume circular beam pipe as a broadband resonator (Q=1) with 1.7 GHz cutoff frequency
- Z_{II}/n = 1.6 (MI longitudinal impedance per harmonic [6, 7]).
- Bunch intensity = 6E10.

Simulations are also carried out with Z_{II}/n = 3.2, 4.8, 6.4, 8 and 24E10 (4 bunch intensity). The longitudinal emittance growth versus Z_{II}/n is shown in the figure 9.

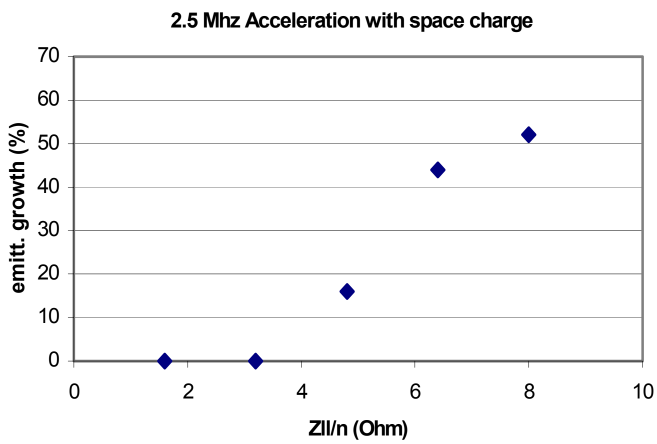
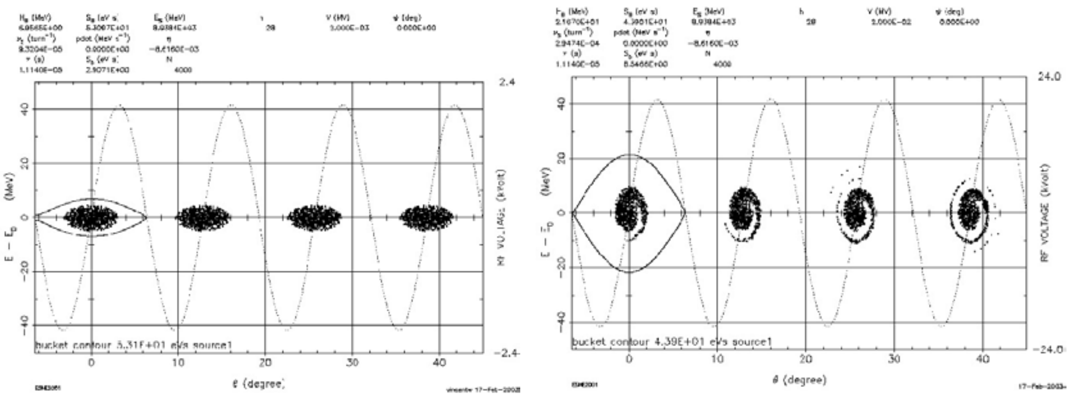


Fig. 9 Longitudinal emittance growth vs. Z_{II}/n.

The space charge voltages are 20 V to 300 V for the 2.5 MHz acceleration and are 3 kV to 8 kV for the 53 MHz acceleration. Within a factor of three of Z_{II}/n =1.6, there is no significant emittance growth. For the case of bunch intensity 24E10 and Z_{II}/n =1.6, the emittance growth is less than 10% and particle loss is less than 1%.

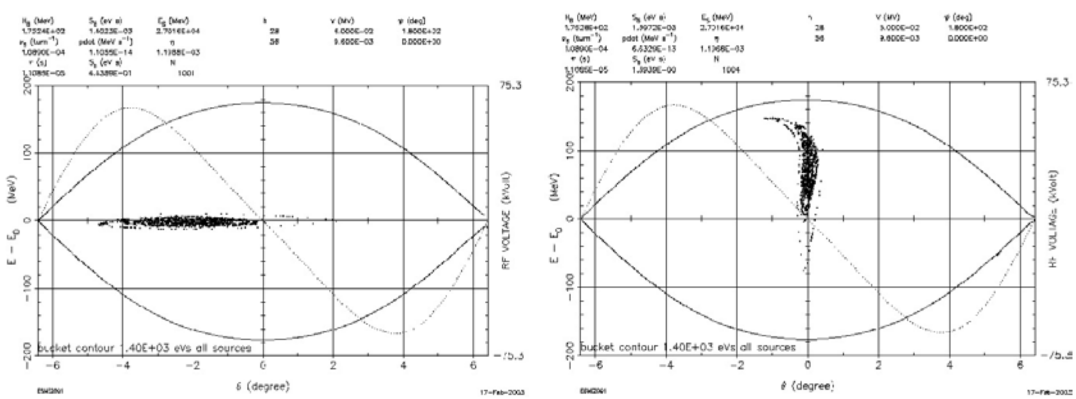
For simulations with beam loading of the 2.5 MHz fundamental mode, four bunches and a single cavity are modeled in ESME. The quality factor and the shunt impedance of the 2.5 MHz cavity are112.5 and 45000 Ohm, respectively [10]. To simulate the total beam loading voltage of five cavities, the shunt impedance is increased by a factor of five.

Some examples of bunch motion are shown in figures 10-12.



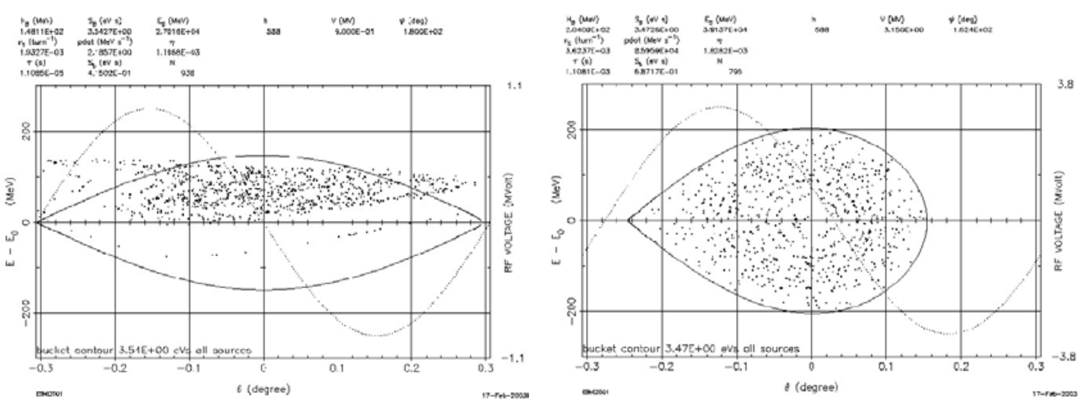
(a) (b)

Fig. 10 (a) Initial distribution. (b) Distribution at the end of the adiabatic bunch shrink (at 0.5 second of the cycle).



(a) (b)

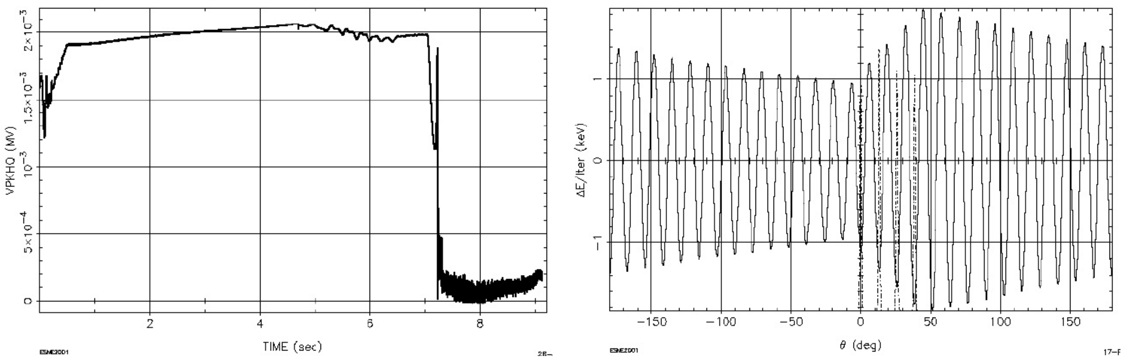
Fig. 11 (a) First bunch at the beginning of the rotation at 27 GeV. (b) First bunch at the end of rotation.



(a) (b)

Fig. 12 (a) 53 MHz capture of the first bunch. (b) 53 MHz acceleration of the first bunch.

Figures 10-12 have shown that beam loading causes significant emittance dilution and phase shift to the bunch distribution. The peak beam loading voltage for the entire cycle as a function of time and an example of beam loading voltage as a function of azimuthal angle along the ring are shown in figure 13. The beam loading voltage at 8 GeV is about



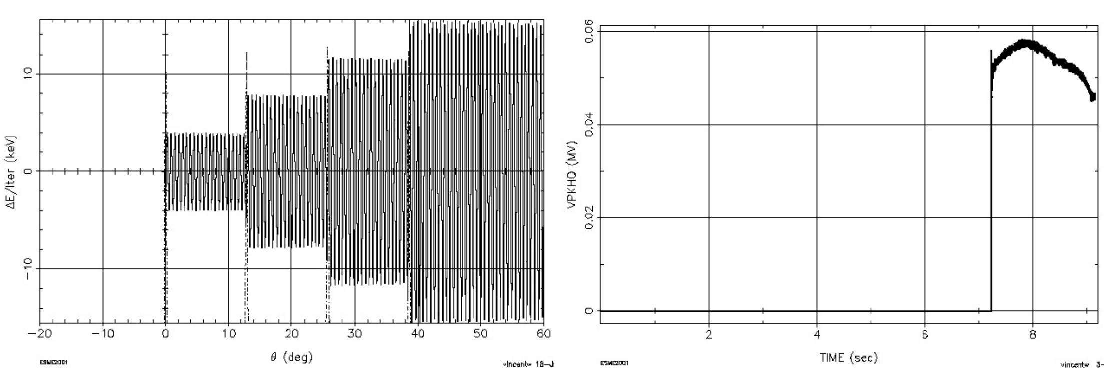
(a) (b)

Fig. 13 (a) Peak beam loading voltage. Ignore voltage after about 8 seconds at which 53 MHz acceleration takes over. (b) An example of beam loading voltage at a particular time along the ring.

900 V and the rf voltage is 2 kV. The phase shift to the rf is about 24 degrees. The peak beam loading voltage during acceleration is 2.1 kV and the rf is in the range of 43 to 60 kV. At 27 GeV the beam loading voltage is about 1.6 kV and the cavity voltage is 4 kV. The phase shift to the rf is 22 degrees. As you can see from figure 11 and 12, the off-centered bunch can't be captured efficiently. Large emittance growth (over a factor of 2) and particle loss are observed. In conclusion, 2.5 MHz beam loading compensation is needed for the 2.5 MHz acceleration scheme.

The 53 MHz beam loading is simulated after the capture at 27 GeV. The shunt impedance and the Q used for the simulation are 520 kΩ and 5000, respectively [12]. To simulate 18 cavities, the shunt impedance is multiplied by 18. Four bunches are simulated with total intensity of 24E10.

The initial beam loading voltage and the peak beam loading voltage for the cycle are shown in Fig. 14 (a) and (b), respectively. During the acceleration, the rf voltage is

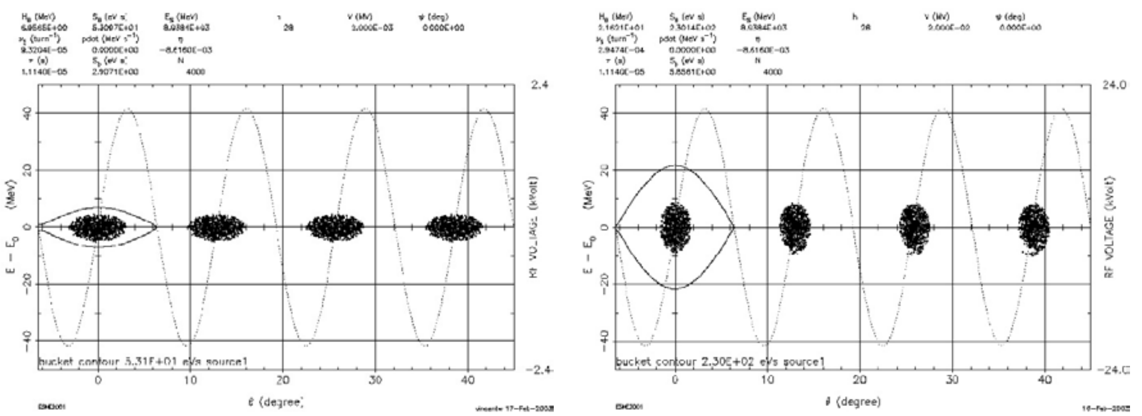


(a) (b)

Fig. 14 (a) The beam loading voltage after the passage of 4 bunches is 16 kV and the rf voltage is 0.7 MV. (b) The peak beam loading voltage during 53 MHz acceleration is about 58 kV and the rf voltage is about 4 MV.

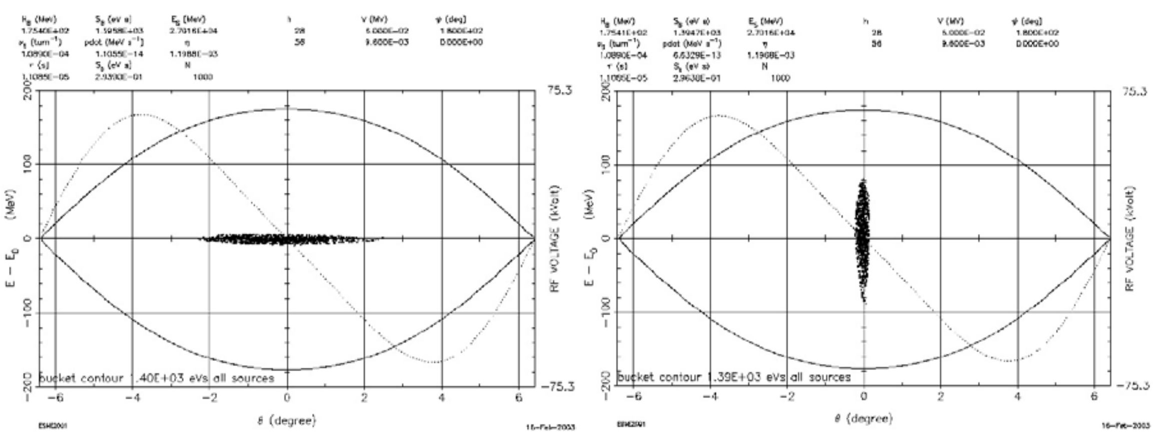
about two orders of magnitude larger than the beam loading voltage. Hence beam loading is not expected to be a problem during 53 MHz acceleration. The emittance growth due to 53 MHz beam loading is a few percents and particle loss is less than 1 %.

The current version of ESME doesn't have beam loading compensation functionality. In order to simulate how much beam loading compensation is needed for the 2.5 MHz cavities, simulations are carried out with reduced cavity Q. The incentive for doing this is because beam loading compensation (feedback) has the effect of reducing the Q of the cavity [10]. Simulation with Q = 11.25 (a factor of 10 reduction from 112.5) for beam loading calculation is performed. Figure 15 through 18 show some examples of bunch motion. At 8 GeV the beam loading voltage is about 570 V when the cavity is at 2 kV.



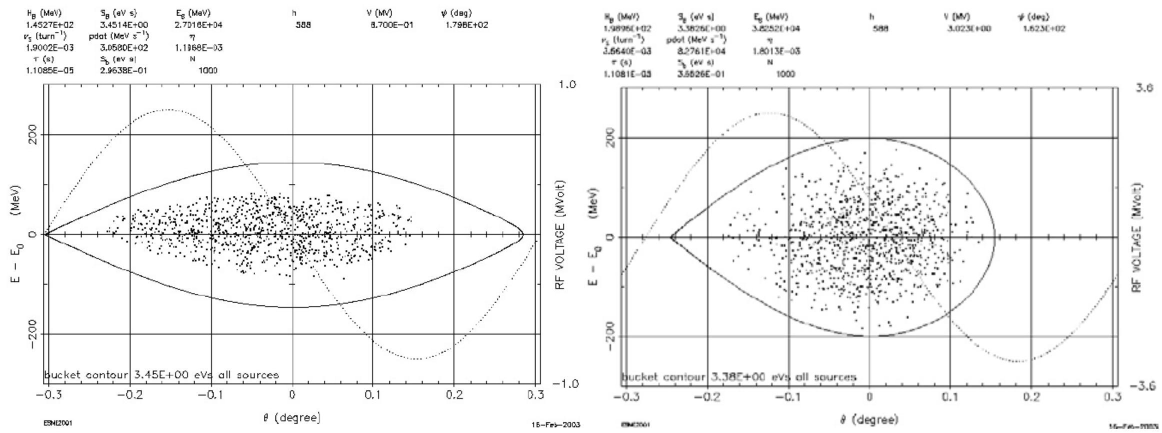
(a) (b)

Fig. 15 (a) Initial distribution. (b) Distribution at the end of the adiabatic bunch shrink (at 0.5 second of the cycle).



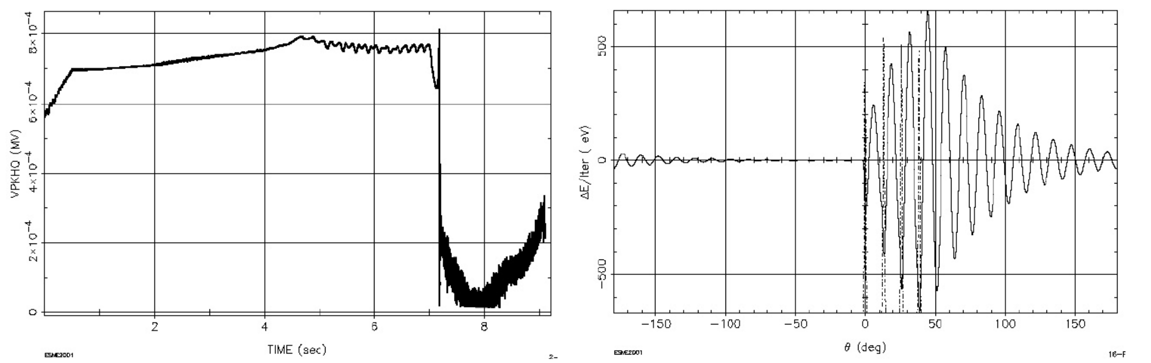
(a) (b)

Fig. 16 (a) First bunch at the beginning of the rotation at 27 GeV. (b) First bunch at the end of rotation.



(a) (b)

Fig. 17 (a) 53 MHz capture of the first bunch. (b) 53 MHz acceleration of the first bunch.



(a) (b)

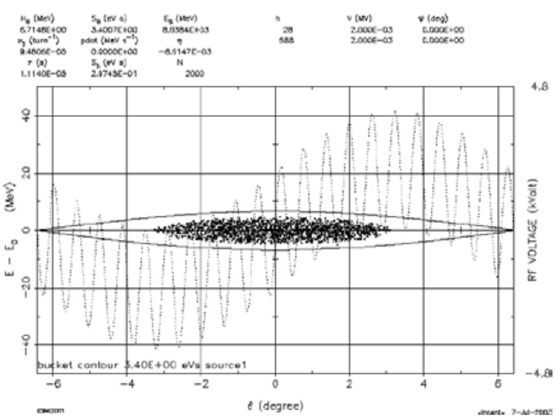
Fig. 18 (a) Peak beam loading voltage. Ignore voltage after about 7.2 seconds at which 53 MHz acceleration takes over. (b) An example of beam loading voltage (before transition) at a particular time along the ring.

At the 27 GeV front porch, the beam loading voltage is about 720 V and the cavity voltage is 4 kV. The maximum beam loading voltage during the 2.5 MHz acceleration is about 800 V. The overall emittance growth is about 27% and the particle loss is minimal. In conclusion, the cavity needs a factor of 10 or more reduction in Q to keep emittance dilution below the 30% level.

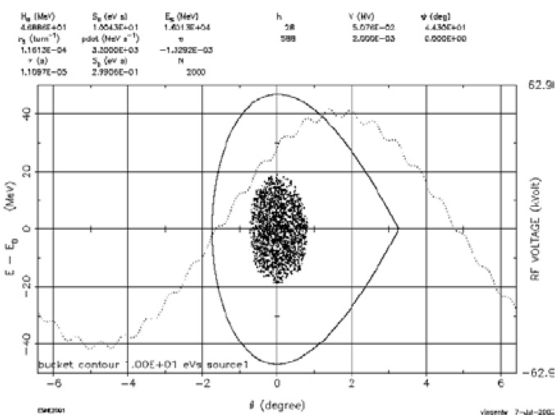
The current feedback beam loading compensation system [10] can reduce the Q by a factor of 4 to 5. The feedback system can possibly be modified to achieve a factor of 10 or more reduction in Q [11]. For the feedforward beam loading compensation system, a 20 dB reduction in the voltage (which corresponds to a factor of 10 reduction) can be achieved [11]. Thus, it seems that the amount of beam loading compensation needed during the 2.5 MHz acceleration is within the capabilities of the feedback and forward compensation systems.

Simulations with different initial emittance (other than 1.5 eVs) are carried out to determine the maximum acceptable injection emittance to Main Injector for acceleration. The studies are done without space charge and beam loading effects. For an initial emittance of 2 eVs, the emittance (95%) growth is 25% and no particles are lost. For an initial emittance of 2.5 eVs, the emittance growth is 13% and 0.6% of the beam is lost. For an initial emittance of 3.4 eVs, the emittance growth is 4% and 6% of the beam is lost. Note that the lower emittance growth for higher initial emittance is due to particle loss.

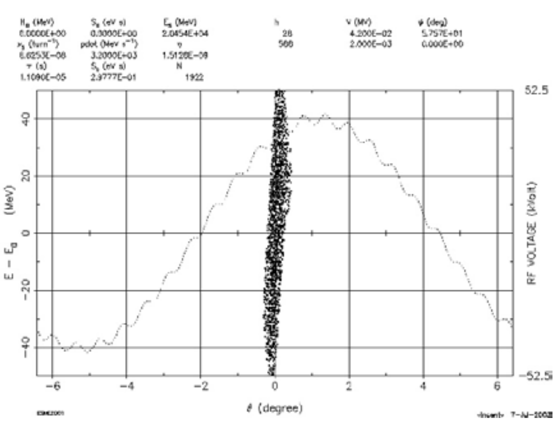
In the Main Injector, the 53 MHz voltage can only be paraphrased down to 1 or 2 kV. To study the effect of this residual 53 MHz voltage on the beam during the 2.5 MHz acceleration (from 8 GeV to 27 GeV), ESME simulation is carried out with 2 kV of constant 53 MHz voltage in addition to the primary 2.5 MHz voltage program. Figure 19 shows the bunch motion at various stages of the acceleration.



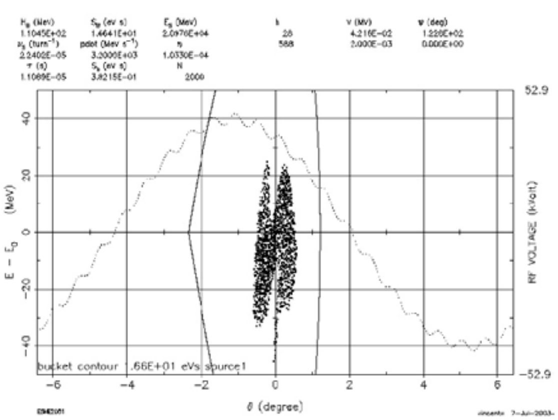
(a)



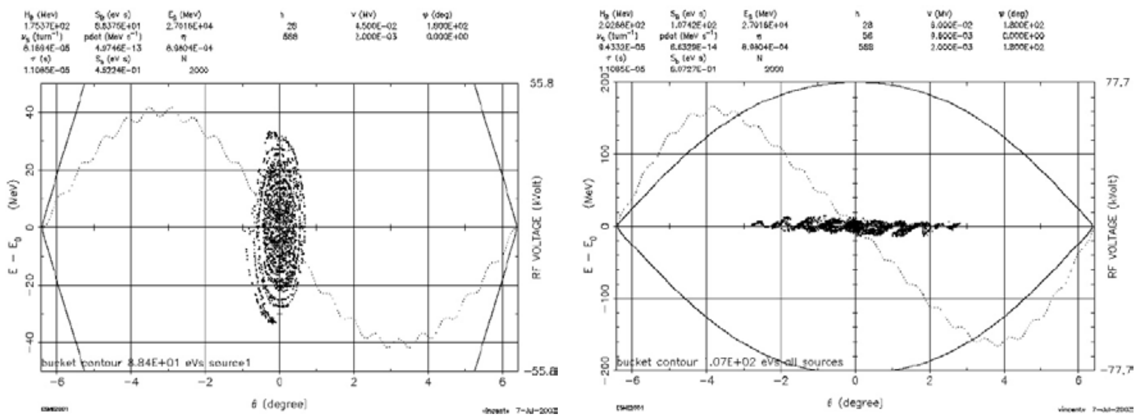
(b)



(c)



(d)

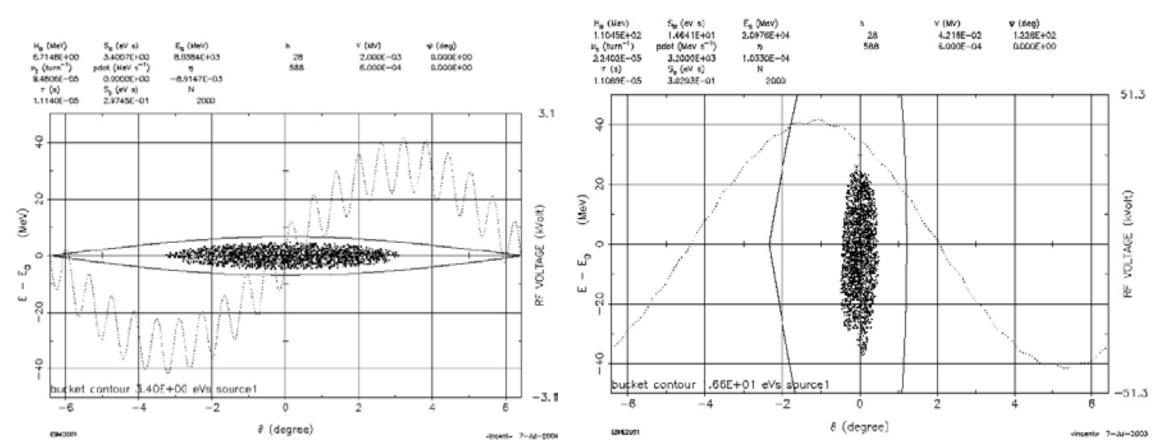


(e) (f)

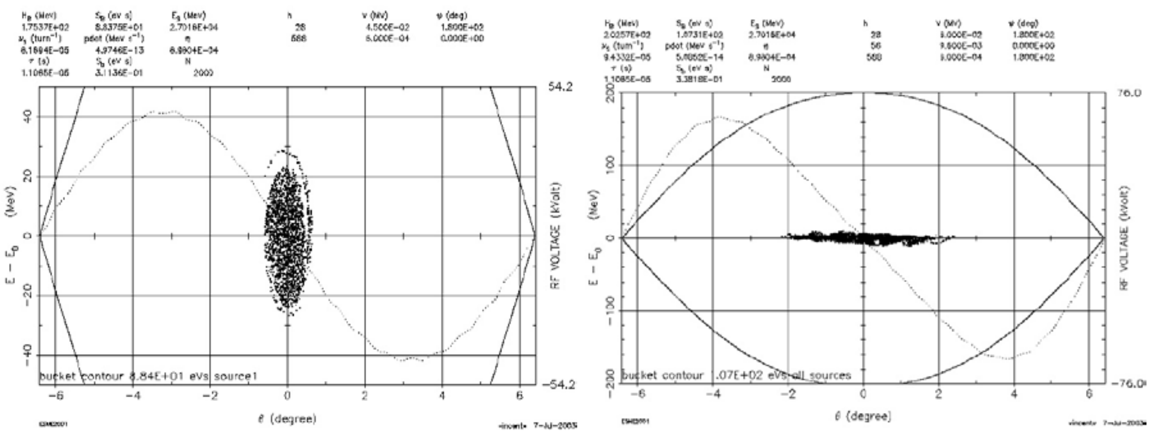
Fig. 19 (a) Initial beam at 8 GeV. (b) Acceleration before transition. (c) At transition before phase jump. (d) After transition. (e) At 27 GeV front porch before rotation. (f) At the beginning of the second rotation.

As one can see from plots (c) and (d), the 53 MHz modulation to the 2.5 MHz voltage has adverse effect to the bunch. At transition (plot (c)), the bunch length is comparable to the 53 MHz bucket length. The bunch is very sensitive to the 53 MHz structure in the rf wave form. In the region of transition crossing, there is large bucket mismatch. The bunch develops into two prongs (see plot (d)). Emittance growth is observed afterward during acceleration. Plot (e) and (f) show the bunch at the 27 GeV front porch. The bunch has 53 MHz structure as expected. This creates additional emittance dilution. For the entire cycle, the emittance growth is over a factor of two. The particle loss is about 5%. Therefore, it is advantageous to reduce the 53 MHz voltage as low as possible or raise the 2.5 MHz voltage to smooth out the 53 MHz structure in the RF wave form during the 2.5 MHz acceleration.

Simulation is carried with 600 V of 53 MHz voltage. Figure 20 illustrates the effect of the reduced 53 MHz voltage. As seen in plot (b), the bunch doesn't develop a two prong



(a) (b)



(c) (d)

Fig. 20 (a) Initial bunch at 8 GeV. (b) After transition. (c) At 27 GeV front porch before rotation. (d) At the beginning of second rotation.

structure after transition. Consequently, the emittance dilution is much less (see plot (c)). The 53 MHz structure in the bunch is also much less (plot (d)). The emittance growth for the cycle is 29% and no particle is lost.

Acknowledgments

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