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Simulation of Space Charge Effects and Transition Crossing in the Fermilab Booster*

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Abstract

The longitudinal phase space program ESME, modified for space charge and wall impedance effects, has been used to simulate transition crossing in the Fermilab Booster. The simulations yield results in reasonable quantitative agreement with measured parameters. They further indicate that a transition jump scheme currently under construction will significantly reduce emittance growth, while attempts to alter machine impedance are less obviously beneficial. In addition to presenting results, this paper points out a serious difficulty, related to statistical fluctuations, in the space charge calculation. False indications of emittance growth can appear if care is not taken to minimize this problem.

Introduction

The longitudinal phase space simulation program ESME[1] has been configured to study various effects in the Fermilab 8GeV Booster accelerator. This paper outlines results of simulations in the vicinity of transition crossing; in particular space charge and wall impedance effects are included and found to be of primary importance. Several quantities in these simulations are shown to agree with recent careful measurements, and from this starting point predictions are made of the results of adding γ_T jump and impedance reducing schemes to the machine.

Simulations of Current Machine

In Figure 1 is shown the distribution in phase space of the particles used in these tracking studies. This distribution is generated 3.5ms before transition and encompasses .02 eV-sec of longitudinal emittance (95%); the RF bucket is shown for comparison. This bunch is acted upon in a turn by turn manner by the RF accelerating potential. The voltage curve is as used in practice; the phase is adjusted in such a manner as to maintain synchronization with the magnetic guide field, and also includes a simulation of radial feedback circuitry. The bunch is also affected by space charge fields and interaction with a wall impedance. The latter is given by the sum of a measured frequency dependent term for magnets together with a smoothly varying function at frequencies beyond the reach of the measurements, and resonant terms, again as measured, for the RF cavities. The space charge and impedance effects depend on the total charge assumed present in a single bunch (as opposed to the number of particles used for tracking, which of course is much lower). For this purpose a value of 2.1×10^{10} particles per bunch is used, a typical Booster operating intensity.

The form into which this particle distribution has evolved at about 1.2ms after transition is presented in Figure 2. This shape, reminiscent of a spiral galaxy, is obtained in these simulations under a wide variety of circumstances as long as the space charge force is included. The voltages due to the space charge and wall effects reach as high as 130KV per turn, with variation across a bunch of 190KV; the

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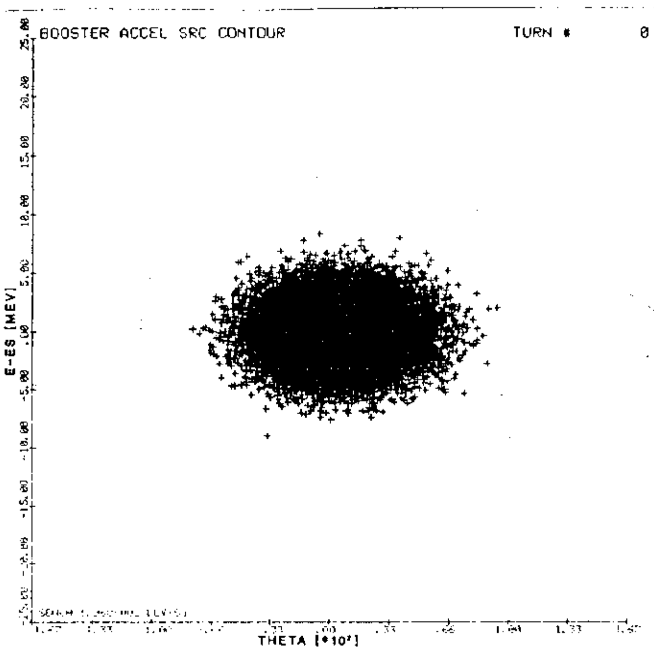

Figure 1. Bi-gaussian random generated phase space distribution of the particles used in these tracking simulation studies. The horizontal axis represents the angular position of the particle in the accelerator at a time when one moving synchronously with the guide field crosses zero. The vertical axis is the difference between the particle energy and that of the synchronous particle.

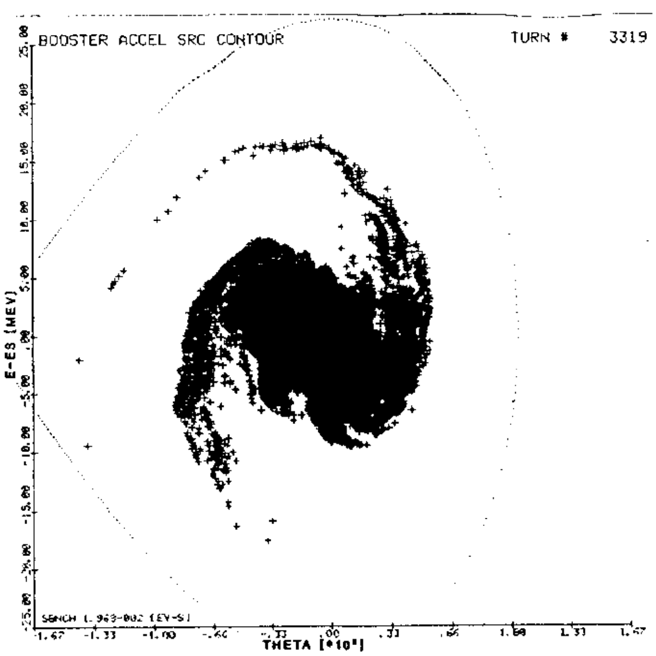

Figure 2. The phase space distribution after transition with current operating conditions and moderate intensity.

applied RF voltage for comparison is 900KV. The measurement which can be made of the actual beam, as opposed to the simulation, is of the charge distribution passing a beam pickup as a function of time. What is often observed in this case is bunch breakup, with double or multiple peaking of the charge distribution. A careful study of the simulation, with plots made every few turns in the vicinity of transition, shows that the projection of phase space on the position axis (a plot essentially equivalent to the hardware measurement) shows similar behavior. Included as Figure 3 is one of the more striking examples of such plots. The observed double peaking appears and disappears depending on the orientation of the spiral in the phase space plot.

From an accelerator physics perspective, the parameter which is adversely affected by the above noted phenomenon is longitudinal emittance. For the particle intensities used here, the observation is that emittance growth is negligible before transition, totals about 100% in that region, and increases only slowly thereafter. Shown as the solid curve in Figure 4 is the emittance as a function of time for the simulation. To be precise, what is plotted is the phase space area enclosed by taking the second moment of the two dimensional distribution, and multiplying by six so that the value corresponds roughly to a 95% emittance value. The plot behaves irregularly during and after transition crossing; however one might infer a growth of about 120%, in adequate agreement with observation.

A remark is appropriate at this point concerning a serious technical problem in the simulation of the space charge force. This force is proportional to the slope of the particle density as a function of position. This slope has been found to be easily influenced by statistical fluctuations in the particle distributions. These fluctuations lead to random space charge forces, and these forces over time affect the particles in such a manner as to cause apparent emittance growth. The parameters used in the simulations shown are that 40000 particles are generated and tracked on each turn, and for the slope calculations are placed in 128 bins for the single bunch under consideration. This binning criterion sets a limit on beam fine structure which can be observed. The emittance growth seen in the figure below transition is believed to be almost entirely due to this simulation artifact. The parameters used have been arrived at in a compromise between desire to limit this incorrect emittance growth and the need to keep computer time reasonable.

There is another parameter for which comparisons between simulations and actual operation can be made, the mean energy loss per particle per turn. This parameter has been measured to be 20 KeV at Booster extraction time. In simulation its calculation results from an appropriate folding of the bunch shape with the real part of the wall impedance. The program yields values in the range of 20-30 KeV for times after transition. A possible 25% discrepancy is not unreasonable considering the difficulty in making impedance measurements as a function of frequency for the entire accelerator.

Simulations have also been made of operation at the Booster record intensity of about 4.2×10^{10} particles per bunch. In this case the emittance growth at transition increases to .09 eV-sec and many particles are forced close to the bucket boundaries. Although the loss of beam is negligible in this simulation, the space charge effect alone can be seen to prevent intensities from increasing much beyond this current record value. (In practice problems are observed at various points in the cycle when operating at such intensities. The time shortly after transition is identified as one such point.) Shown in Figure 5 is the phase space distribution after transition for high intensity conditions.

Simulation of Proposed Improvements

Two schemes have recently been considered to improve Booster operation. The first is the construction of a γ_T jump, which changes the lattice parameters so rapidly that the beam spends a minimum amount of time near transition. The second scheme involves the installation of strips to shield the beam from magnet pole faces, thus reducing the overall machine impedance.

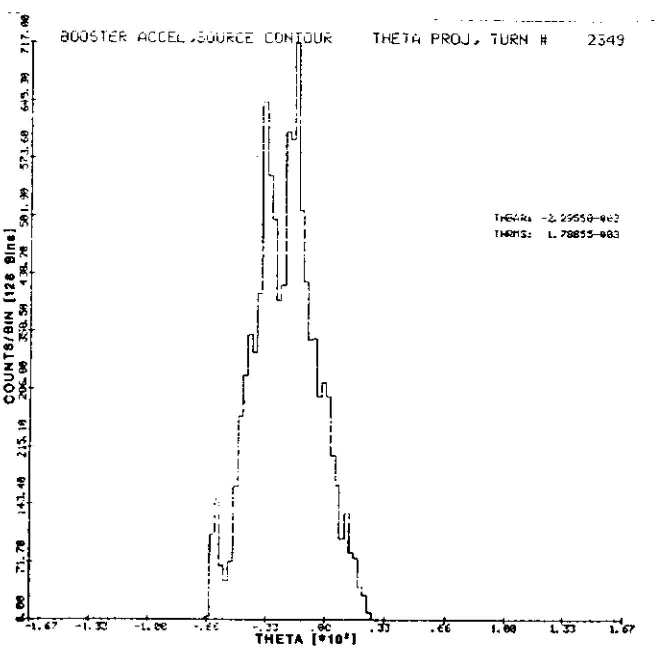

Figure 3. Theta projection of phase space distribution at a time shortly after transition. The multiple peaking agrees with observation.

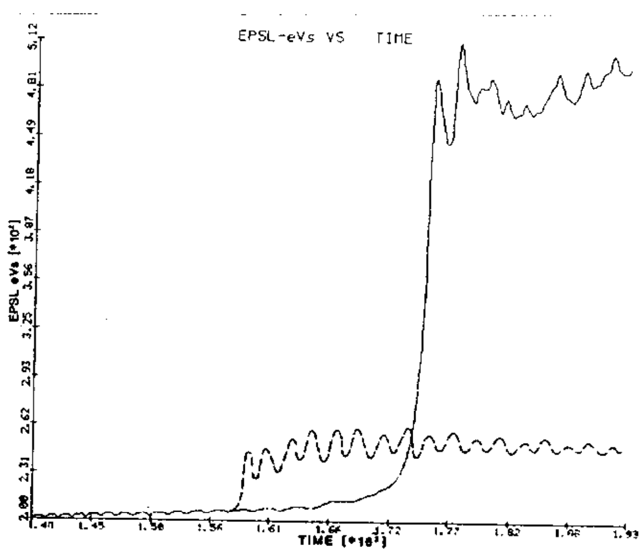

Figure 4. Simulated emittance as a function of time. The solid curve is for current operating conditions and moderate intensity; the dashed curve differs only by the inclusion of a γ_T jump.

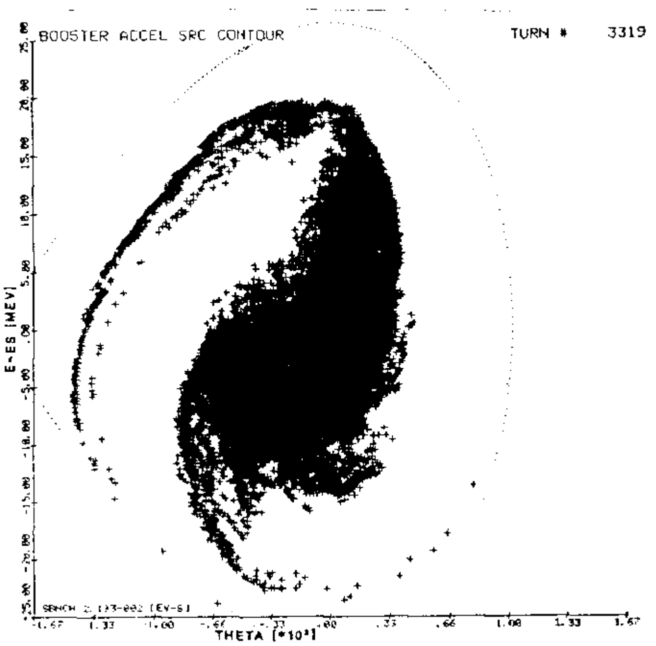

Figure 5. The phase space distribution after transition with current operating conditions but at record intensity.

The parameters of the jump used in this simulation are that γ_T decreases linearly by one unit over 100 μs. It then reverts exponentially with a time constant of 2.5 ms to its original value. A problem observed with such a scheme is that large bunch length oscillations appear at times after the fast γ_T jump. Ng[2] has calculated that these oscillations can be minimized by adjusting the time in the cycle at which the jump occurs. Considering the parameter η, rather that γ_T, one might naively expect that a jump symmetric about zero would be optimal as the beam would remain at the maximal possible distance from the conditions at transition. He finds however that a delay in the jump time, allowing η to approach zero more closely from low energy and departing farther from zero at high energy is preferable. These calculated results are not duplicated in the current work. The simulation includes effects of non-linear RF forces, wall impedances, and feedback loops, which were not included in the calculation. The bunch length oscillations are observed but with a time-dependent amplitude not seen in the calculation. In the simulation the oscillations have an amplitude whose initial value is somewhat greater than that predicted and which decreases somewhat as the jump time is moved earlier; however greater emittance growth accompanies these decreased oscillations so that no clear preference is seen for any jump other than that symmetrical about zero in η.

Shown as the dashed curve in Figure 4 is the emittance vs time with the γ_T jump included. The improvement over the traditional operating conditions is clear. As these Booster protons eventually feed the Tevatron, the lowered emittance growth observed may ultimately translate into improved luminosity for collider operation. Runs of the high intensity beam conditions with the γ_T jump included indicate similar significant improvements.

Attempts to reduce the magnet impedance by introduction of metallic strips between the particle paths and the pole faces lead to less striking improvements according to these studies. However at high intensity the after-transition emittance with γ_T jump is reduced by 10%. Also, beam excursions which severely test the radial feedback system are greatly reduced, presumably leading to easier and more reliable operation.

Conclusions

Carefully performed simulations of longitudinal variables in the Fermilab Booster near transition energy lead to reasonable quantitative agreement with measurements. The simulations are able to predict the results of various changes which might be made in machine operating conditions.

References

[1] J.A. Maclachlan, this conference, Paper L28

[2] King-Yuen Ng, Fermilab Report FN-436, 0302-0000, September 1986