Emittance Growth in MEB and Its Control

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Abstract

There are effects in the Medium Energy Booster (MEB) of SSC which will lead to growth of the transverse beam emittance. Among them are space charge, decoherence due to residual chromaticity and nonlinearity of field, coherent instabilities, etc. This paper numerically estimates the strength of these effects on the beam stability and the emittance growth. To ensure that the emittance growth is within the stringent emittance budget of the SSC accelerator complex, a few feasible cures have been planned. Their improvements on beam quality are also described in this paper.

I. INTRODUCTION

The transverse emittance preservation in the SSC accelerator complex is essential to achieve the luminosity goal. A very stringent emittance budget has then been imposed on the MEB; namely 0.6 π mm-mrad (rms. normalized) at injection and 0.7 π mm-mrad at extraction. The allowed increase is only 17%. Therefore, care must be taken in our design study to: include all possible sources which might contribute to the emittance growth, predict their strength, and implement some precautions to control this growth within the above limitation. Table 1 lists the main beam parameters of MEB.

In general, the following factors in the MEB should be included in the study for the emittance growth control:

A) multipoles in magnetic field;

B) space-charge tune spread at injection and transition;

C) decoherence due to residual chromaticity and nonlinearity of fields when the beam is injected with transverse errors;

D) coherent instabilities, etc.

A computer simulation of the beam has been performed to examine the effect of the factor A on the emittance growth. Five thousands particles in the six-dimensional Gaussian distribution are tracked up to four thousands turns after injection. All multipoles in the dipoles and quardrupoles as well as alignment errors, which are specified by SSC documents[1], are included in the calculation. The result does not show any significant increase in either horizontal or vertical emittances. The discussions of other factors (B, C, D) will be the subjects of the following paragraphs, which are based on either computer modeling or scaling law.

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

Table 1
Main beam and machine parameters of MEB

Parameters	Value
Injection Momentum	12 GeV/c
Extraction Momentum	200 GeV/c
Harmonic Number	792
Bunch Spacing	5 m
Bunch Density	1×10^{10} proton
95% Bunch Area at Injection	0.038 eV-Sec.
Bucket Area at Injection	0.43 eV-Sec.
Chromaticity Natural	-31.0
$\frac{\sigma_p}{p}$ at injection	2.16×10^{-4}
Transition Gamma	23.28
Betatron Tune(H)	25.43
Betatron Tune(V)	25.46

II. SPACE CHARGE TUNE SPREAD AND CHOICE OF OPERATING POINT

The repulsive electric force produced by the beam itself often can not be ignored, resulting in the betatron tune of the particles being depressed. The maximum tune shift from the bare tune is given by Laslett formula for the Gaussian distribution:

$$\Delta\nu = -\frac{r_p n_t B_f}{4\pi\beta^2\gamma^3\epsilon^{un}}$$

where, r_p is the classical proton radius, n_t is the total number of particles in the ring, β and γ are the Lorentz factors, ϵ^{un} is the unnormalized beam emittance, and B_f is the bunching factor, which is the ratio of peak beam intensity to the average around the ring. For MEB the value is -0.083 at injection and becomes smaller at higher energy. This shift may make the beam cross lower-order resonances. In a real machine, where errors exist, the particles can be lost, or the beam emittance can grow when the tune approaches one of these resonances. Fig. 1 shows the tune diagram near the fractional operating points of MEB. The initial operating point was tentatively set to (25.42, 25.38). The location on the tune diagram is marked by the top square. Due to space charge effects the tunes of the particles spread out downward on the plane. The particles near the center of bunch are depressed the most, reaching point on the diagram (25.34, 25.30); very close to the horizontal third-order resonance. While some outer particles in the beam would fall in the vertical third-order region. The beam simulation code, SIMPSONS[2] indicates that there is an increase in both horizontal and vertical emittances, and this increase in the vertical plane can reach approximately 10% when the MEB injection process is finished. In addition, there is another problem found with the operating point. That is, the tune distribution with particle amplitude is spread downward along the diagonal on the diagram due to the effect of the difference resonance $\nu_x - \nu_y = 0$, where, ν_x and ν_y are the horizontal and vertical tunes, so that the linear aperture is reduced much.

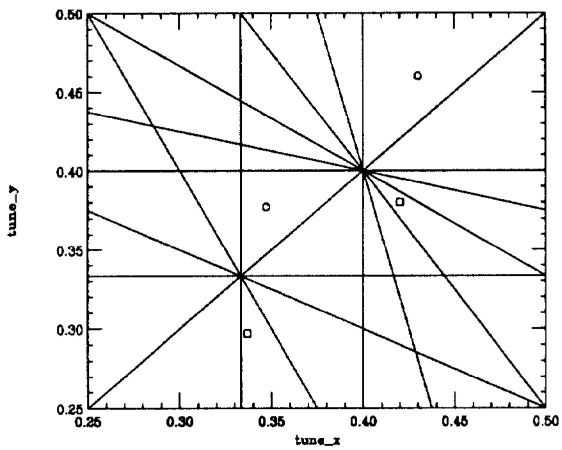

Figure 1. Tune diagram near the operating points

To solve the above problems, the operating point has been adjusted from (25.42, 25.38) to (25.43, 25.46) as marked by the circle on the diagram. Third integer resonances are hereby avoided, even with space charge included. The simulation shows no significant growth in emittances.

When the beam crosses the transition energy, the bunches become much shorter. The bunching factor increases from 8.1 to about 65. Using the Laslett formula expressed above, the maximum tune shift due to space charge is 0.19, twice the value at injection. However, this expression does not recognize the component of the beam size due to the combination of dispersion and momentum spread. At transition this contribution to beam size is larger than the contribution from betatron motion. Otherwise the shift is even smaller than the injection value according to our calculation. Fig. 2 shows the transverse emittance evolution around transition with space charge and its image force included. Both horizontal and vertical emittance are stable except that there are compensatory emittance oscillations between the two planes. It is obviously caused by difference resonance.

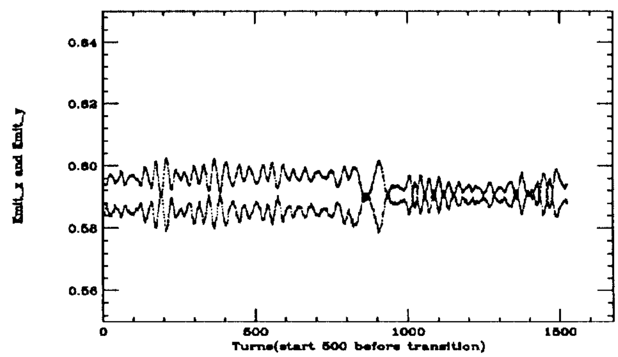

Figure 2. Transverse emittance around transition

III. DECOHERENCE AND SUPPRESSION OF INJECTION ERROR

When a beam is injected with a departure from the closed orbit, it begins making betatron oscillations about the closed orbit. If the beam contains a spread of tunes, the motion will decohere as the individual betatron phases of the particles disperse. The phase space distribution of the beam spreads from a localized bunch to an annulus which occupies all betatron phases[3]. In MEB, the injection errors come from the LEB extraction system(kicker, septum) , MEB injection kicker and other elements on the beam transmition line. The statistical errors at the injection point are 0.7 mm in horizontal plane and 1.1 mm in vertical plane. The emittance dilution factors, which are defined by

$$F \equiv \frac{\delta\epsilon}{\epsilon} = \frac{\pi}{2}\frac{\Delta x^2(\beta\gamma)_{Lorenz}}{\beta\epsilon},$$

will be 20% in horizontal plane and 85% in vertical plane. Here, Δx is the equivalent injection error given above. The β function at the injection point are 51 m and 14.4 m in the both planes, respectively.

A damper has been specified for killing the coherent oscillation due to the injection errors. The damping speed should be much faster than the dilution time which is expressed by $\tau_D = \frac{1}{\Delta\nu}$. Where $\Delta\nu$ is the tune spread in the beam. In MEB, there are two sources of the betatron tune spread: transverse nonlinearity (tune as a function of particle amplitude) and nonzero chromaticity (tune as a function of momentum spread through $\Delta\nu_c = \xi\frac{\Delta p}{p}$). According to our simulation, the latter effect dominates. Suppose residual chromaticity is -5.0, then the emittance will be diluted completely within 310 turns. So an damping period of 25 turns is good enough for limiting the emittance dilution.

IV. COHERENT INSTABILITIES AND CURES

The interaction between the charged beam and the environment (wake field) might excite many different coherent oscillations in the beam. In some case it can lead to the transverse emittance growth and even a beam loss. By their original mechanism, the coherent instabilities in MEB may be classified into three categories: single bunch caused by the broad band impedance, couple bunch by the high-Q impedance of RF cavity and resistive wall by the non-purely conductive vacuum pipe. A code ZAP[4] has been used to estimate the threshold value or growth time of these instabilities. Around transition, where the theoretical mode used in ZAP no longer works well, the six-dimensional tracking code SIMPSONS is used, as well as the two-dimensional code ESME[5].

Many efforts have been made in the design to reduce the broad band impedance of MEB. These include shielded bellows and screened pump ports, etc. As a result of these efforts, the broad band impedance is expected to be reduced to 1.65 MOhm/m. Our study indicates that there is big margin of the impedance budget in comparison with the threshold value of the single instability(36 MOhm/m at the injection).

However, the beam in MEB does have a problem with the coupled bunch instability which is caused by the transverse high-mode impedance inside RF cavity. Fig. 3 gives the growth time of the instability over the full RF cycle. As denoted by the bottom curve in the figure, the growth time is about 1 second. This obviously can not be tolerated, considering the beam will circulate in the ring for 5 second. A HOM damping scheme is then proposed. A significant improvement on growth time can be seen in the top curve in Fig. 3 where a few major impedance peaks have been damped by a factor of 10.

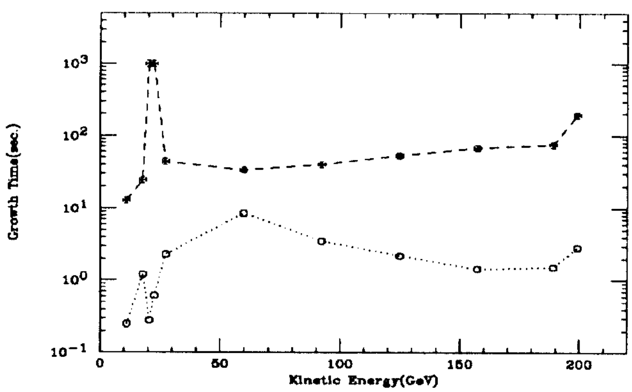

Figure 3. Transverse couple bunch instability growth time

The resistive-wall instability belongs to family of the coupled bunch instabilities. It may be triggered in many different modes. For MEB, the lowest mode frequency is 41KHz with the fastest growing time of 2.5ms and the highest mode is about 30MHz. To suppress this instability, a feed-back system has been planned. It will consists of beam position monitor, electronic processing, time delay, filter and kicker. To guarantee the functionality, the main properties of the system have been set as follows:

bandwidth: 30KHz-15MHz
deflection: 3.2μrad/turn, at P_{inj}=12GeV/c
damping period: 25 turns
acceptance: 2mm
peak power: 700W

Special attention has been paid to the transition region of the MEB where the dynamic process is nonadiabatic. As the phase slip factor, $\eta \equiv \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$, approaches zero, less Landau damping is provided. Since the chromaticity is not zero in a real machine, a large shift in coherent mode frequencies, which is estimated through $\omega_\xi \equiv \frac{\xi}{\eta}\omega_0\nu_0$, occurs, where ξ is chromaticity, ω_0 is the revolution frequency and ν_0 is the betatron tune. So a strong coupling of m=0 mode to the resistive part of the broad band impedance can be expected, as indicated by Jacques Gareyte[6]. One cure to this head-tail instability is a chromaticity-jump. By reversing the sign of the chromaticity before and after transition correctly, one can guide the shift to the right direction so to avoid the coupling. This technique has been successfully implemented in both the main ring of Fermilab and the PS at CERN.

V. CONCLUSION

In the MEB, there will be many different sources which might lead to a transverse emittance growth. To limit this growth within a stringent tolerance is very challenging. Studies indicate that, with a good machine design and some necessary precautions it is still possible to achieve the goal of the SSC: high luminosity with a low transverse emittance.

VI. REFERENCES

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