BEAM DYNAMICS SIMULATIONS IN THE RAPID CYCLING MEDICAL SYNCHROTRON*

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Abstract

The Rapid Cycling Medical Synchrotron (RCMS) [1] accelerator is under conceptual design at BNL. We report the results of the beam dynamics studies in the current design RCMS ring lattice with simulation program ORBIT++ [2]. In this paper, the designed RCMS ring lattice, the important physical parameters and the simulation program employed in this study are overviewed. The major elements and the numerical parameters included in the simulations are listed and discussed. The evolution of longitudinal beam properties, such as bunch length, bunch height and particle distributions, under RF voltage ramping are studied. The simulation results of the 6D beam dynamics during acceleration including phase space and emittance evolution are presented. Finally, the space charge effects such as tune shift and emittance growth in the RCMS ring are investigated and discussed.

1 SYNCHROTRON RING OF RCMS

The RCMS [1] is a second generation proton therapy synchrotron offering more flexible performance in a simpler, lighter and more robust implementation. The RCMS can reduce the typical treatment time and at the same time will reduce the risk of dumping a large amount of radiation into the patient [3]. The synchrotron ring of RCMS has two arcs and two straight sections. Each arcs is built with 7 combined function magnets that are dipole magnets with the poles slightly tilted to create a quadrupole component. The primary physical parameters of the synchrotron ring are listed in Table 1 [4] and its lattice functions are shown in Fig.1 [3].

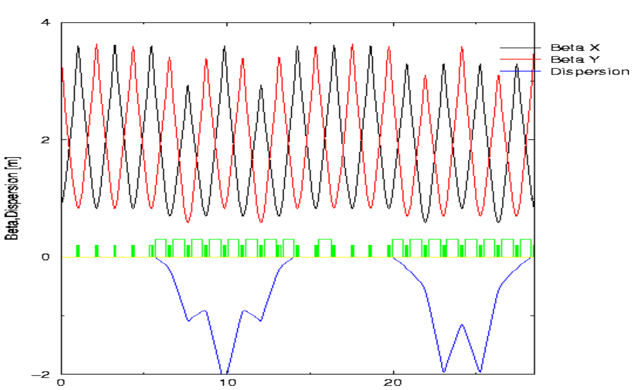

Fig. 1 lattice functions in synchrotron ring of RCMS.

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Table 1 Primary parameters of RCMS

Injection kinetic energy	7 MeV
Min. extraction energy	70 MeV
Max. extraction energy	250 MeV
repetition rate	30 Hz
Min. protons per bunch	1.0 x 10^7
Max. protons per bunch	1.7 x 10^9
Circumference, C	28.6 m
Number of FODO cells	13
Half-cell length	1.1
Dipole magnet length	0.682 m
Quadrupole magnet length	0.14 m
Horizontal tune, Qx	3.093
Vertical tune, Qy	3.102
Max. horizontal beta-x	3.64 m
Max. vertical beta-y	3.64 m
Max. dispersion	2.17 m
Horizontal chromaticity	-2.18
Vertical chromatisity	-2.64
Transition gamma	2.391

2 BEAM DYNAMICS SIMULATIONS

This simulation study was performed with the 6D tracking code ORBIT++ [2] which is a later version of the original ORBIT developed by ORNL and BNL collaborations [4-7]. All the physical quantities used in the simulations are chosen to be as close as possible to the specifications in the current design of RCMS [1,3].

In this study, total number of 1.7×10^{19} protons are injected at 7 MeV kinetic energy into the synchrotron ring of RCMS, and accelerated to 250 MeV kinetic energy. The RF voltage, synchrotron frequency, synchrotron phase, synchronized particle kinetic energy and the relativistic β value as function of time during RF ramping are in accelerated The RF ramping are present in Fig. 2. The resulting longitudinal beam properties during acceleration were obtained with full 6-D simulations. The bucket length, the bunch length and bunching factor during the acceleration is presented in Fig.3. The bucket height and the bunch height is presented in Fig.4. While, The bucket area and the bunch area is presented in Fig.5. The strong schycro-betatron coupling was evident in the beams in this low-energy synchrotron.

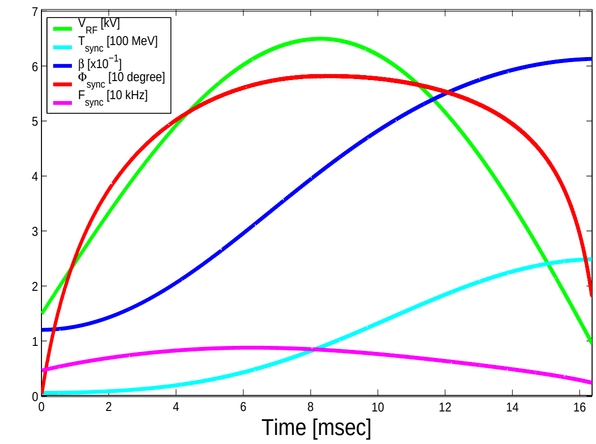

Fig 2. RF Ramping.

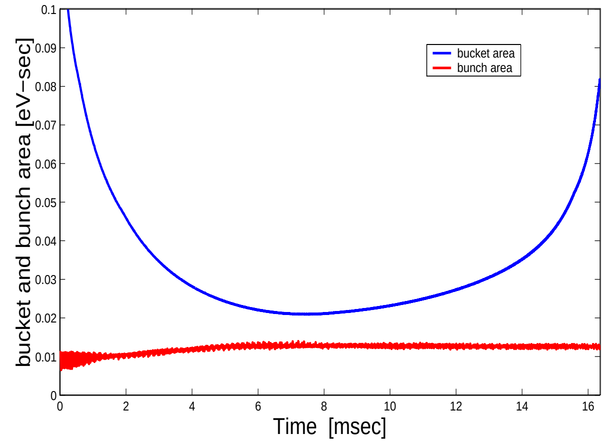

Fig. 5 Bucket area and bunch area during RF ramping.

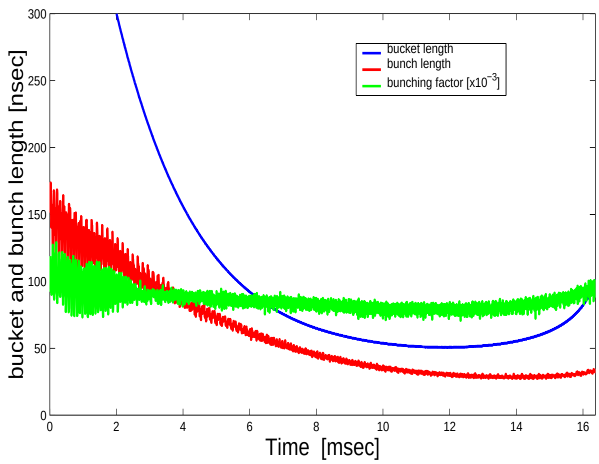

Fig. 3 bucket length, bunch length and bunching factor during RF ramping.

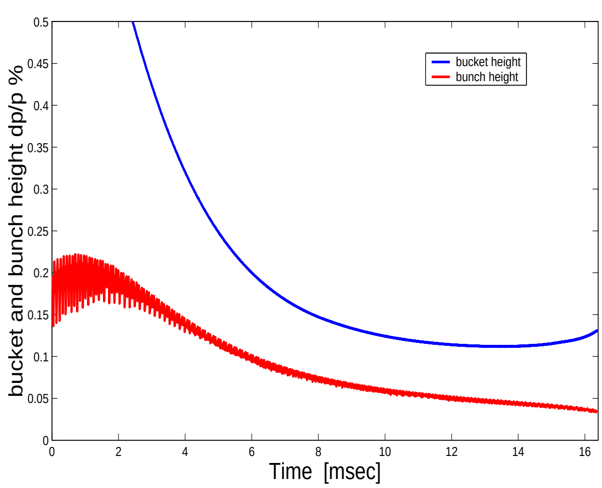

Fig. 4 Bucket height, bunch height during RF ramping.

The current RCMS RF system is designed for beam injection with bunch length of 100 nsec and energy spread of 32 keV. The maximum and RMS emittance evolutions during the acceleration are shown by the blue lines in fig. 6 and Fig. 7. In order to investigate the possible cost reduction of RF system, we also study the transverse emittance evolutions of proton beams with various injection energy spreads ΔE_{inj} and injection bunch lengths L_{bunch}. Together with the case of the current design, in Fig.6 and Fig.7 three other cases are also presented. They are (a) L_{bunch}=80nsec, ΔE_{inj}=32keV; (b) L_{bunch}=100nsec, ΔE_{inj}=16keV; and (c) L_{bunch}=80nsec, ΔE_{inj}=16keV. Fig. 6 shows transeverse maximum beam emittance evolution of four different during RF ramping. The horizontal maximum emittance is shown in the top figure, and the vertical maximum emittances are shown in the bottom figure.

The space charge tune-shift can be estimated with the analytical formula [8]:

$$\Delta\nu = \frac{Nr_p}{2\beta\gamma^2\varepsilon_N B_f}, \qquad (1)$$

where r_p=1.54×10^{-18} m is the classical proton radius, N is the total number of proton in the bunch, ε_N is the normalized beam emittance, B_f is the bunching factor, β and γ are relativistic factors. The largest spaced charge tune shift in RCMS is at the injection. Its value from the simulation results is 0.09 which agrees with the estimate with the analytical formula (1).

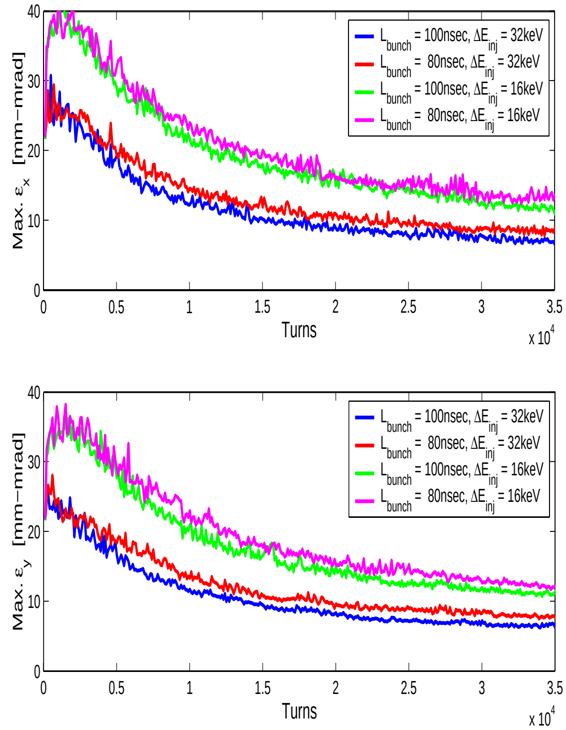

Fig. 6 Transeverse maximum beam emittance evolution during RF ramping. The horizontal maximum emittance is shown in the top figure, and the vertical maximum emittances are shown in the bottom figure.

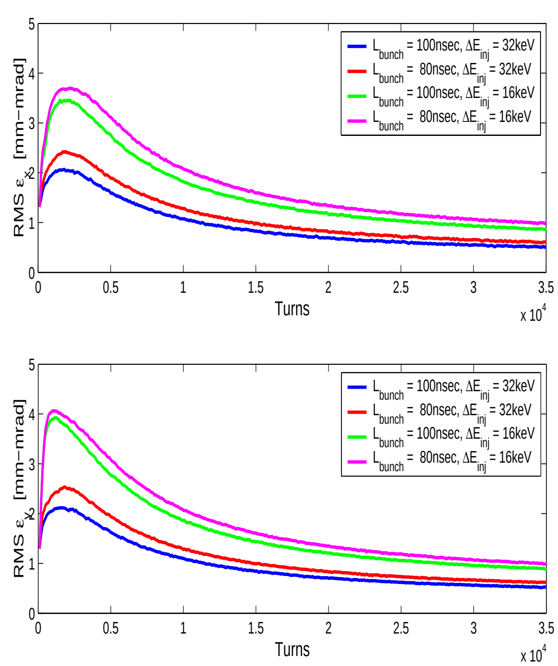

Fig. 7 Transeverse RMS beam emittance evolution duringRF ramping. The horizontal RMS emittance is shown in the top figure, and the vertical RMS emittances are shown in the bottom figure.

4 DISCUSSION AND CONCLUSION

Space charge forces, magnet error and misalignment, each play very important role in beam emittance growth, halo/tail formation and beam loss. When all these sources are present, the effect can be largely enhanced depending on the choice of working points. This simulation did not include misalignment and the magnet errors. These errors also cause emittance growth. Previous beam dynamics simulation studies on SNS accumulator ring [9] has shown that the space charge may exit the resonance due to misalignment and magnet errors. We also should be careful with beam aperture especially at the initial stage of the ramping.

6 REFERENCES

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