STUDY ON RESISTIVE WALL INSTABILITY IN CSNS/RCS

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Abstract

Rapid Cycling Synchrotron of the China Spallation Neutron Source is a high intensity proton accelerator, with average beam power of 100kW. The collective effects caused by the coupling impedance may be the limit to beam power. The impedance estimation for components on beam line shows that the resistive wall impedance and its instability are more serious than any others. Based on the impedance budget, the instability is theoretically estimated. And a simple resistive wall wake field model is used to simulate the bunch oscillation and the growth rate instability. In this model, the continuous resistive wall wake field is equivalent to a point wake field and long bunch is sliced into many micro-bunches. By tracking the dynamics of the macro-bunches, the transverse growth rate are obtained and the result are analyzed.

INTRODUCTION

The China Spallation Neutron Source (CSNS) accelerators consists of an H^- linac and a proton Rapid Cycling Synchrotron (RCS). RCS is designed to accumulate and accelerate proton beam from 80MeV to 1.6GeV. The extracted 100 kW beam strike the neutron target with repetition rate of 25Hz. The RCS lattice adopt a triplet cell based 4-fold structure[1]. Table 1 shows main parameters of RCS.

Table 1: Main Parameters of CSNS/RCS

Parameters	Values
Circumference/m	227.92
Inj. energy/MeV	80
Ext. energy/GeV	1.6
The length of Stainless steel chamber/m	140
Average beta function(H/V)/m	9/10
Nominal tunes(H/V)	4.86/4.78
Natural chromaticity	-8.27/-4.64
Bunch number	2
Particles per bunch	1.46e13

About half of vacuum chamber in CSNS/RCS is made of stainless steel, such as the drift chamber. The total length for the stainless steel chamber is about 140 meters. The resistive wall impedance mainly comes from the vacuum chamber.

The beam loss in RCS caused by resistive wall instability may be one of the limits to reach the design beam power. Especially, at the low-energy end of each cycle, the resistive wall instability is much more serious. The detailed study on resistive wall instability in RCS is necessary to the design of accelerator.

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In the first part of the paper, according to the analytical formula and impedance model on resistive wall instability, the instability is estimated. In the second part, a simple simulation model is introduced and with the tracking on macro-particles, the bunch oscillation is simulated. Based on the analytical and simulation results, the way for depressing the resistive wall instability is introduced in the last part of the paper.

THEORETIC ESTIMATION ON THE RESISTIVE WALL INSTABILITY

Because of wake field caused by the resistive wall of the vacuum chamber, the transverse motion of bunches can be expressed as[2,3]

$$\ddot{y}_0(t)+\omega_\beta^2 y_0(t) = -\frac{N_p r_p v}{\gamma T_0}\sum_{k=0}^{\infty}[W_1(-kC-\frac{C}{2})y_1(t-kT_0-\frac{T_0}{2}) + W_1(-kc)y_0(t-kT_0)] \quad (2.1)$$

the two bunches are specified by indices 0 and 1, ω_β is the frequency of betatron motion, W_1 is transverse wake function, N_p denotes the number of particles in a bunch, γ is relative energy factor, v is velocity of particle, $T_0 = 2\pi/\omega_0$, ω_0 denotes angular revolution frequency, and the summation over k sums the wake field over all previous revolutions.

By solving the equation (2.1) in frequency domain, the complex mode frequency shift and growth rate of transverse resistive wall instability are obtained[4]

$$(\Delta\omega_\beta)_{coh} = -\frac{i r_p k_b N_p v Z_T}{2\omega_\beta \gamma T_0^2}, \qquad \frac{1}{\tau} = \frac{N_p k_b r_p \omega_0^2}{2\pi\beta\gamma c Z_0}\beta_{av}\,\mathrm{Re}(Z_T). \quad (2.2)$$

where r_p denotes classical radius of proton, k_b expresses the bunch number, Z_T is transverse impedance. $\mathrm{Re}(Z_T)$ denotes the real party of transverse impedance, Z_0 is impedance of free space, β_{av} is average beta function, c is the velocity of light and β is the relativistic velocity factor.

According to equation (2.2) and the CSNS/RCS resistive wall parameters, the growth time at the injection and extraction energy can be estimated, which are about 5.2ms and 8.3ms respectively. Transverse resistive wall instability for CSNS/RCS, which may cause beam loss, is analytically derived in a simple condition. More detailed study of resistive wall with the simulation program is necessary.

Considering the damping effect from natural chromaticity, the growth time with natural chromaticity becomes

$$\frac{1}{\tau} = \frac{N_p k_b r_p \omega_0^2}{2\pi\beta\gamma c Z_0}\beta_{av}\,\mathrm{Re}(Z_T)F_m(\omega_\xi). \qquad (2.3)$$

$F_m(\omega_\xi)$ is form factor. The growth time with different natural chromaticity is show in figure 1.

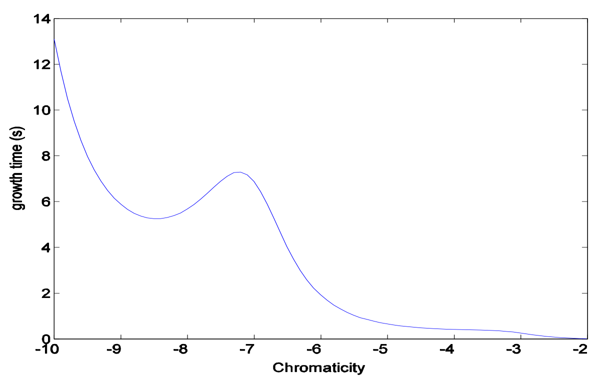

Fig 1: Injection transverse growth time versus chromaticity.

SIMULATION ON RESISTIVE WALL INSTABILITY

Simulation Model

Resistive wall wake field can be obtained by solving Maxwell equation in general case and wake function is expressed as[5]

$$W_{nj\perp} = -\beta^{3/2} c Z_0 \frac{1}{\pi^2 b^3}\sqrt{\frac{\mu_r c}{\sigma}}\left[\frac{1}{|z|^{1/2}} + \frac{3}{8}\frac{b^2 - \frac{3}{2}x^2}{\gamma^2 |z|^{5/2}}\right]. \qquad (2.4)$$

where, b is the radius of chamber, x is the transverse offset, $|z|$ is the distance from beam to test charge, σ is the permittivity, μ_r is the relative permeability of vacuum pipe.

The equation of motion with wake field is shown in equation (2.1). The transfer matrix is

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{i+1} = \begin{pmatrix} \cos(2\pi\nu_{x,y}) & \beta\sin(2\pi\nu_{x,y}) \\ -\frac{1}{\beta}\sin(2\pi\nu_{x,y}) & \cos(2\pi\nu_{x,y}) \end{pmatrix}\begin{pmatrix} x \\ x' \end{pmatrix}_i + \begin{pmatrix} 0 \\ dx' \end{pmatrix}. \qquad (2.5)$$

Where β is average Courant-Snyder parameter of ring, $\nu_{x,y}$ is horizontal or vertical tune, dx' is transverse kick of resistive wall.

In this model, the resistive wall wake field is simply to one point on RCS and justified to lump resistive wall kick at one point in the ring[6]. Beam will see the kick when it passes the point in each revolution. In addition, the multi-turn long range wake will be seen by particles; as a result, the wake must be cut for some reasonable turns in simulation. So the kick seen by beam in a turn is

$$dx' = \sum_n \sum_j -\frac{eq < \overline{x_{nj}} > W_{nj\perp} N_{nj} L}{\beta^2 E}. \qquad (2.6)$$

where, L is total length of stainless steel, E is the energy of beam, N_{nj} is number of macros of nth turn jth slice, $< \overline{x_{nj}} >$ is average value of macro-particles, $W_{nj\perp}$ is transverse wake function of test charge, the bunch is considered to be divided longitudinal into many slices.

Including the synchrotron motion in the model, the synchrotron motion of bunch can be expressed by transfer matrix form as

$$\begin{pmatrix} \Delta z \\ \delta \end{pmatrix}_{i+1} = \begin{pmatrix} \cos(2\pi\nu_s) & \frac{\eta\beta c}{\nu_s\omega_0}\sin(2\pi\nu_s) \\ -\frac{\nu_s\omega_0}{\eta\beta c}\sin(2\pi\nu_s) & \cos(2\pi\nu_s) \end{pmatrix}\begin{pmatrix} \Delta z \\ \delta \end{pmatrix}_i. \qquad (2.7)$$

where, Δz is longitudinal relative distance, δ is momentum spread, ν_s is longitudinal tune, η is slippage factor. RF acceleration should be considered during RCS program, which can be expressed as[7]

$$\begin{aligned} \Delta E_{i+1} &= \Delta E_i + eV(\sin(\phi_i) - \sin(\phi_s)), \\ \phi_{i+1} &= \phi_i + \frac{2\pi h\eta}{\beta^2 E}\Delta E_{i+1}. \end{aligned} \qquad (2.8)$$

where h is harmonic number, ϕ_s is the phase angle for a synchronous particle with respect to the RF wave, ϕ_i is the phase angle for off-momentum particle.

The transverse offset of beam can be obtained every turn, and then growth time can be obtained.

Natural chromaticity can damp instabilities. The natural chromaticity is considered in tracking. In this case, the tune of each macro is

$$\nu_{x,y} = \nu_{x,y} + c_{x,y}\delta_{x,y}. \qquad (2.9)$$

$\nu_{x,y}$ is particle real tune, $\nu_{x,y}$ is designed tune of particle, $c_{x,y}$ is natural chromaticity.

The beam energy in RCS changes turn by turn. The above tracking can be only applied to a short time interval of injection, with not energy change. It is vital to include the energy increasing in the simulation.

Simulation Result

In the simulation, a bunch is sliced into 50 pieces and each bunch is represented by 3000 macro particles. Horizontal beta and vertical beta are 9 meters and 10 meters respectively. The bunch is tracked about 10000 turns, which is much longer than the injection time. The simulation shows the transverse growth time is about 6.3ms and 9.2ms for injection and extraction energy respectively, which are consistent with the analysis result in part 2. The oscillation amplitude of bunch during the injection and extraction are shown in figure 2.

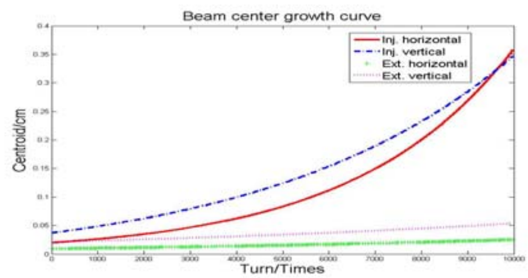

Figure 2: Injection and extraction transverse bunch centre variety versus turn in CSNS/RCS. The red, blue and green, pink lines are injection horizontal, vertical and extracted horizon, verticality plane respectively.

In simulation shown in the figure 2, beam energy is fixed during tracking, which is not accurate for CSNS/RCS because of energy ramping every turn. Considering the actual process of injection and extraction, simulation is shown in figure 3. The instability growth time of vertical and horizontal directions are 7.4ms. One should note that the growth curve at that time is not exponential. The growth time is obtained by calculating the time when transverse offset increased e(2.71828) times of initial offset.

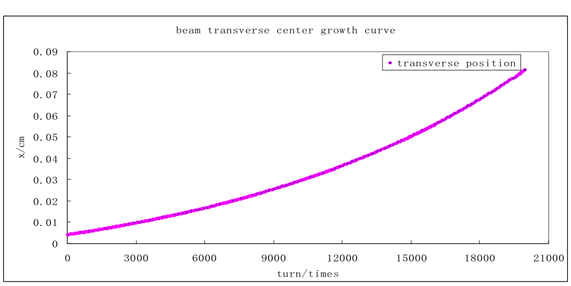

Figure 3: Transverse growth curve versus varied energy.

Radiation damp can weaken resistive wall transverse instabilities in electron machines, however, there is no radiation damping in proton machines. Natural chromaticity can depress collective instabilities. Including the chromaticity in particle tracking, which caused the maximum deviations in two directions are about 0.04 and 0.06, and the instability is depressed. The simulation result is shown in figure 4.

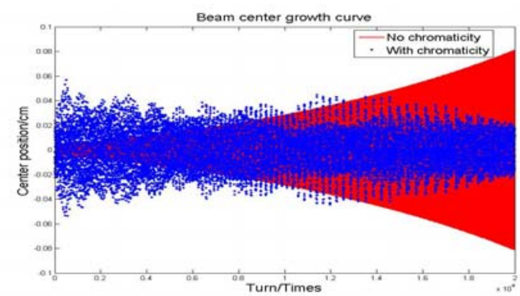

Figure 4: Varied energy resistive wall instability growth curve vs chromaticity in CSNS/RCS. The red curve is transverse growth no chromaticity, the blue curve denotes growth with natural chromaticity.

CONCLUSION

The simulation result during the phase of injection and extraction, 6.3ms and 9.2ms, agree well with theoretical calculation result — 5.2ms and 8.3ms. Tracking rapid cycling synchrotron program, the growth time is about 7.4ms. The instability can not be neglected if there is no other damp mechanism. In fact, resistive wall transverse instability is depressed by natural chromaticity. Injected growth time with chromaticity is much larger than RCS cycle period. The transverse resistive wall instability can be depressed while the chromaticity effect is considered. The instability should be further study in case of chromaticity correction.

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