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STUDY OF THE STABILITY OF LONGITUDINAL BEAM DYNAMIC OF CEPC FOR UNEVEN FILLING

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Abstract

PDR is a choice of CEPC design scheme, at any given time will contain a train of 50-70 bunches populate adjacent buckets and the remaining buckets unfilled. A consequence of an uneven filling scheme in the storage ring is that within train the synchronous phase will vary from bunch to bunch. This paper is to describe the tracking of the stability of longitudinal beam dynamic for CEPC, with the aim of including the main effects affecting the beam dynamics (i.e. the bunch-by-bunch feedback, the effect of the HOMs, the synchrotron radiation)..

INTRODUCTION

Table 1: The Machine Parameters of CEPC Partial Double Ring Scheme

Parameters	
Beam energy[GeV]	120
Beam revolution frequency [MHz]	5475.46
Energy spread total[%]	0.16
Number of IP	2
Circumference[km]	54
SR loss/turn[GeV]	3.1
Bunch number	50
Bunch current[mA]	16.67
Bunch length[mm]	6
Momentum compaction[10^{-5}]	3.4
RF Voltage[GV]	6.87
RF frequency[MHz]	650
Harmonic number	117081
Quality factor	4E10
Coupling factor	1.82E4
RF frequency[MHz]	650
Harmonic number	117081
Shunt impedance[MΩ]	5.72E2

CEPC is a circular electron-positron collider operate at 240GeV center-of-mass energy with a circumference of 54 km, serve as a Higgs factory. The parameters of CEPC is shown in Table 1.The main constraint in the design is the beam lifetime due to beamstrahlung(a process of energy loss by the incoming electron due to its interaction with the electron (positron) bunch moving in the opposite direction) and the synchrotron radiation power, which should be limited to 50MW per beam, in order to control the AC power of the whole machine. A new scheme called partial double ring was development recently and crab waist was adopted on CEPC. The layout of the CEPC partial double ring scheme is shown in Figure 1. The main advantage of crab waist is that the beam-beam limit can be significantly increased. At any given time, the ring contains a train of 50-70 bunches. Within the train bunches populate adjacent buckets and there is an extreme long gap that extends over 11731-11001 buckets. The time structure of bunch train is shown in Figure 2. A consequence of such uneven filling scheme is that within train the synchronous phase will vary significantly from bunch to bunch. For superconducting cavities with heavy beam loading, the transient effects result from fierce beam-cavity interaction should be carefully explored to provide information to the low level feedback system to ensure the accelerator can operate stabilized. In this paper we will study the beam loading of fundamental mode ignore the effect of other high order modes.

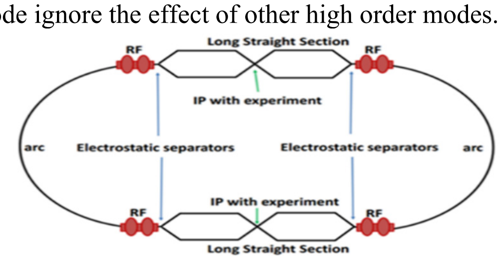

Figure 1: The layout of CEPC partial double ring.

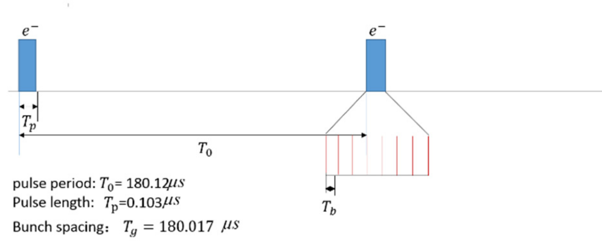

Figure 2: Time structure of bunch train.

COMPUTER SIMULATION OF THE BEAM LOADING

Tracking Model

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To find the steady-state fundamental voltage and phase along the bunch train, we model each bunch as a macroparticle. The main purpose of this paper is to explore the effects of main cavity on the bunch train and the status of the asymmetric fill pattern. The difference equation for the synchrotron oscillations of each bunch can be expressed as [1],

$$\varepsilon_{j+1} = (1 - 2\lambda_{rad})\varepsilon_j + \frac{1}{E}\left[eV_g(\phi_{j+1}) + eV_b - U_0\right] \quad (1)$$

and

$$\phi_{j+1} = \phi_j + 2\pi\alpha h\varepsilon_j \quad (2)$$

where ε is the relative beam energy deviation, and ϕ is the bunch phase with respect to the nominal synchronous phase. λ_{rad} is the radiation damping rate expressed in units of the rotation frequency and 1U0 is the radiation loss per turn. V_g and V_b are the generator and beam-induced voltages in the main cavities.V_g is given by

$$V_g(\phi_i) = \sin(\phi_i + \phi_0 + \psi) \quad (3)$$

where ϕ_0 is the stable phase for the rf voltage,ψ is the tuning angle of the rf cavity.

The relation of tuning angle to the detuning of the cavity is

$$\tan\psi = 2Q_L \frac{f_{res} - f_{rf}}{f_{res}} \quad (4)$$

where $Q_L$is load quality factor.

Beam-induced Voltage

We assume that the beam-cavity energy exchange at a single point in the ring. In the tracking code each bunch is modeled as a macroparticle of charge q. Under this condition it is possible to simulate only the "rigid" oscillation that, however, are the most dangerous for the beam stability. When a charge q crosses the cavity, it perturbs the total voltage. The induced voltage of each mode depends on the shunt impedance R_m, the quality factor Q_m and the angular frequency $\omega_m of\ the\ mode$,

$$v_m = -2\frac{\omega_m R_m}{2Q_m} q = -2k_m q \quad (5)$$

where $k_m$is the loss factor and m labels the cavity number. In this paper we mainly focus on the beam loading of the fundamental mode (m=0). The induced beam voltage resonance with the frequency of fundamental mode and decay in magnitude by a factor $e^{-\tau}$, where $\tau = \frac{2Q}{\omega_0}$ is the cavity filling time and ω_0 is the fundamental resonance angular frequency. In storage ring, the particle bunches go through the cavity periodically, so we should consider the cumulative build up of the beam voltage. The voltage induce by the bunches is found from the difference equation

$$V_{b,i+1} = V_{b,i}e^{[j\omega_0 - \frac{1}{\tau}]\Delta t} - 2kq \quad (6)$$

Δt is arrive time between the current (ith) bunch and previous (i-1th) bunch given by

$$\Delta t = \frac{\phi_{t,i} - \phi_{t,i-1}}{\omega_0} + T_b \quad (7)$$

T_b is the spacing of bunches which is equivalent to the number of buckets between the bunches multiplied by main rf period.

For the purpose of taking the bunch length into consideration, assuming a Gaussian distribution, the shunt impedance is corrected by a factor [2-7],

$$\exp[-(\omega_m\sigma_t)^2] \quad (8)$$

where $\omega_m$is the resonance angular frequency of the mode and the $\sigma_t$is the RMS bunch length. The build up of beam induced voltage is shown in Figure 3.

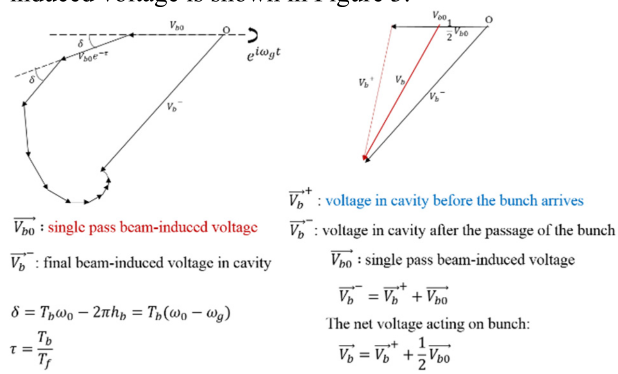

Figure 3: The build up of beam induced voltage in cavity.

From the fundamental theorem of beam loading, when a point charge crosses a cavity, it leaves behind a voltage V_{b0}, the point charge itself decelerated by $V_{b0}/2$. Therefore the final effective beam-induced voltage given by

$$V_{t,i} = V_{t,i} - (-k_0 q_i \exp[-(\omega_m\sigma_t)^2]) \quad (9)$$

SIMULATION RESULT

Use the difference equation of the synchrotron motion we can track the bunch motion of arbitrary number turn by turn. In this section we present the result of beam loading of CEPC partial double ring scheme with a train of 50 bunches adjacent in the fill pattern.

Assuming that the cavity is operated at optimum tuning frequency and the revolution period $\boldsymbol{T_r}$ is much shorter than the filling time of the cavity $\boldsymbol{T_f}$,namely $\boldsymbol{T_r}/\boldsymbol{T_f} \ll \boldsymbol{1}$,the phase shift of the bunch train caused by the long gap can be estimated analytically by [8]

$$\Delta\theta_{1N} \approx \frac{-2kq}{V_{c0}\sin\phi_0}\left[\frac{(N-1)N_g}{N+N_g}\right] \quad (10)$$

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where k is loss factor , q the charge per bunch,N the bunch number per train ,$N_g$the number of missing bunch in the gap. The analytical bunch phase shift is 4.6969 degree.

The author is still working on debug the code, the simulation result cannot be shown for the moment.

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