DOUBLE RF SYSTEM FOR LANDAU DAMPING AND ROBINSON INSTABILITY

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Abstract

Design consideration of a double RF system for Landau damping of a longitudinal instability is presented. Experimental results of the system constructed in SOR-RING are briefly described together with an analysis of Robinson instability additionally induced in the system.

Introduction

A longitudinal coupled bunch instability induced in SOR-RING increases the bunch length and transverse width of the electron beam, and accompanies a slow fluctuation of the peak current of the beam bunch and also of the synchrotron radiation.[1] In order to suppress the instabilty by Landau damping an additional cavity with the second harmonic RF frequency was installed. The instability was really suppressed by the double RF system, but this success was limited below a beam current about 30 mA. Above this current another phase instability was induced, which can be explained by Robinson instability. The second instability was suppressed by a phase feedback in the double RF system up to a beam current of 110 mA.[2] In this paper are presented the design principle of the double RF system and the analysis of the Robinson instability.

Design Consideration of Double RF System

In SOR-RING the bunch lengthening due to a longitudinal instability follows a one fifth power of the beam current I. This can be explained by the ballance of the growth rate of the instability and Landau damping due to synchrotron frequency spread $\Delta\omega_s$. The growth rate is given by

$$\alpha_g = kI/A^3 \tag{1}$$

where k is a constant proportional to coupling impedance and A the half bunch length. The Landau damping is given by

$$\alpha_L \cong (\Delta\omega_s/4) \cong (2/3)\omega_s (A/L_{RF})^2 \tag{2}$$

where L_{RF} is the wavelength of RF frequency.

Synchrotron frequency in double RF system $\Delta\omega_{sL}$ is extremely increased, and the threshold current in this system I_{thL} is determined by

$$I_{thL}/I_{th} = (3/8)(\Delta\omega_{sL}/\omega_s)(A_L/A_0)^3 (L_{RF}/A_0)^2 \tag{3}$$

where A_0 is the bunch length at the threshold current I_{th} without the Landau cavity. Thus, the threshold current in the double RF system can be calculated if we know the synchrotron frequency spread $\Delta\omega_{sL}$ and bunch length A_L.

Electrons make synchrotron oscillation in the following potential (see Fig.1)

$$\Phi(\tau) = \int_0^{\tau} (\alpha/ET_0)(eV(\tau')-U)\,d\tau' \tag{4}$$

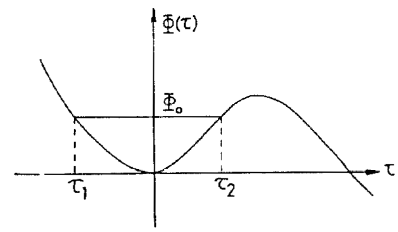

Fig.1 Approximate form of potential $\Phi(\tau)$.

where α is the momentum compaction factor, E the beam energy, T_0 the revolution period, $V(\tau)$ the total RF voltage and U the radiation energy. The oscillation frequency is determined by

$$1/\omega_s(\Phi_0) = \frac{1}{\pi}\int_{\tau_1}^{\tau_2} [2(\Phi_0 - \Phi(\tau))]^{-1/2}\, d\tau \tag{5}$$

Here Φ_0 is a modified electron energy, which takes the following range from the bottom of the potential

$$0 < \Phi_0 < 2(\alpha\sigma_E/E)^2 \tag{6}$$

with σ_E the natural energy spread. The bunch length $A_L = c(\tau_2 - \tau_1)/2$ is determined by the maximum energy Φ_{0max}.

RF voltage in the double RF system is given by

$$V(t) = V_c \sin(\omega_{RF}t + \phi_s) + V_{cL}\sin(n\omega_{RF}t + \phi_L) \tag{7}$$

where V_c and V_{cL} are the peak cavity voltage in main and Landau cavity, and ω_{RF} and n the RF frequency and harmonic number, respectively. The largest spread in synchrotron frequency can be obtained by the condition, $(dV(t)/dt)_{t=0} = 0$;

$$V_c \cos\phi_s + nV_{cL}\cos\phi_L = 0 \tag{8}$$

The potential $\Phi(\tau)$ defined by (4) becomes

$$\Phi(\tau) = (\alpha/ET_0)\{(eV_c/\omega_{RF})[\cos\phi_s - \cos(\omega_{RF}t + \phi_s)] + (eV_{cL}/n\omega_{RF})[\cos\phi_L - \cos(n\omega_{RF}t + \phi_L)]\} \tag{9}$$

In SOR-RING the radiation energy is U=0.72 keV/turn at 308 MeV and the main cavity voltage is V_c=20~25 kV to provide a sufficiently long Touschek lifetime, so that $\phi_s \cong 0$. In the double RF system we choose $\phi_L \cong -\pi$ to get the widest frequency spread. Then for $\omega_{RF}\tau \ll 1$, we find

$$\Phi(\tau) = (\alpha/ET_0)\{(eV_c/2\omega_{RF})(\omega_{RF}\tau)^2(1 - nV_{cL}/V_c) - U\tau\} \tag{10}$$

and the condition (8) becomes

$$V_c \cong nV_{cL} \tag{11}$$

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Thus, the potential $\Phi(\tau)$ is nearly flat at the bottom of the potential.

The synchrotron frequency at each value of Φ_0 in the range of (6) was calculated numerically using the potential (10) for different harmonic number n, from which we get the frequency spread $\Delta\omega_{sL}$ as well as the bunch length A_L. The threshold current was estimated by (3). These are summerized in Fig.2. In case of n=2 the bunch length is the longest and twice of that without the Landau cavity, and the threshold current becomes very high. To make Touschek lifetime as long as possible after damping the longitudinal instability we have selected the harmonic number n=2.

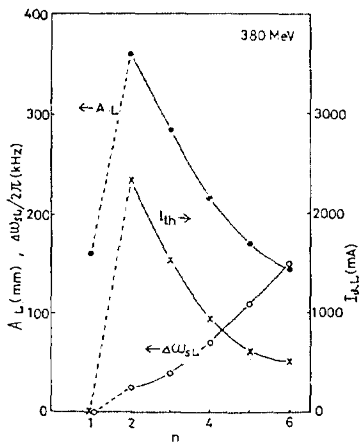

Fig.2 Calculated synchrotron frequency spread $\Delta\omega_{sL}$, bunch length A_L and threshold current I_{thL} for longitudinal instability in the double RF system.

Experiment

A block diagram of the double RF system is shown in Fig.3. The cavity voltage V_c and V_{cL} can be kept constant by feedback loops, and the generator voltages V_g and V_{gL} generated by transmitters, can also be constant by the use of circulators. In this experiment the tuners in the cavities were adjusted manually. The phase ϕ_L of V_{cL} in the Landau cavity can be controlled by using a ballanced mixer with respect to the phases of the beam bunch and generator voltage.

When the phase of V_{cL} was adjusted to the optimum phase $\phi_L \cong -\pi$, the longitudinal instability was suppressed as expected; the coherent modes and the slow fluctuation of the beam bunch were suppressed. But this success was limited below a beam current about 30 mA. Above this current the beam bunch sliped away from the optimum phase with a simultaneous deformation of total voltage as shown in Fig.4. In this situation the Landau damping is no longer effective to suppress the longitudinal instability.

To overcome this difficulty it is necessary to lock the ϕ_L by the phase feedback. Then the longitudinal instability was suppressed up to a beam current of 110 mA, compared with the initial threshold current of 0.24 mA at 308 MeV. In spite of the substantial increase of the threshold current, this is not yet sufficient for practical use.

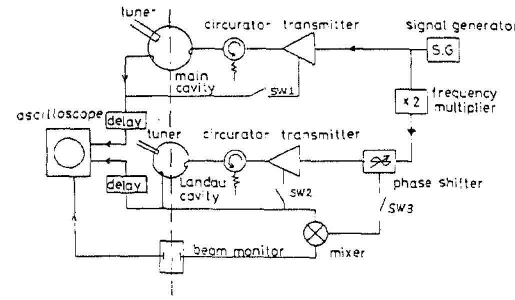

Fig.3 Block diagram of double RF system.

Above the threshold current 110 mA the phase feedback is not sufficient to keep the optimum phase, and the beam bunch fluctuates a little around the optimum phase at about the maximum frequency of the band width in the phase feedback loop. The phase shift becomes faster with increasing the beam current, so that it becomes harder to keep the optimum phase at a higher beam current.

Robinson Instability in Double RF System

There are two kinds of Robinson instability in a bunched beam. The first kind is induced by a dynamic interaction of coherent synchrotron oscillation modes with a sharp coupling impedance of RF cavity. The stability condition above transition energy is determined by the tuning angle of the cavity as follows,[3]

$$\psi < 0 \qquad (12)$$

The angle is defined as $\tan\psi = -2Q_L(\omega_{RF} - \omega_r)/\omega_r$, where Q_L and ω_r are the loaded Q and resonant frequency of the cavity, respectively.

The second kind instability is induced by the relation of revolution period for a change of energy gain of the bunched beam. Stability is obtained when the beam bunch locates on the decreasing phase of the generator voltage,[3,4]

$$dV_g/dt < 0 \quad \text{or} \quad 0 < \phi_g < \pi \qquad (13)$$

Here ϕ_g is taken with respect to the beam bunch. The condition (13) implies that the stability is obtained if the vector of the generating voltage V_g locates on the upper half plane of the phase diagram.

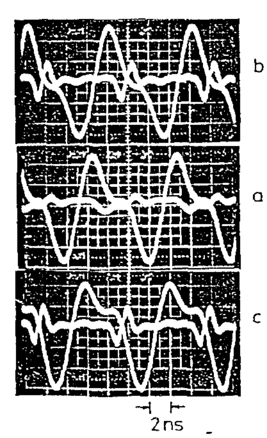

Fig.4 Phase slip of beam bunch above a threshold current for Robinson instability. The figure shows the total voltage and beam bunch in time derivative. a;unstable, b,c;stable

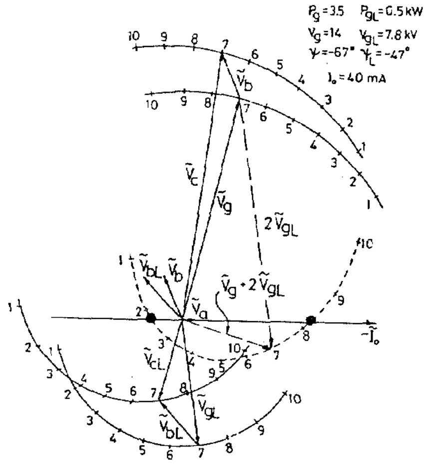

Fig.5 Phase diagram of generated voltage V_g, V_{gL}, induced voltage V_b, V_{bL} and cavity voltage V_c, V_{cL} with respect to the beam current $-I_0$. The same number on the curves satisfy the equilibrium condition (15).

In the double RF system the stability is determined by the change of total generator voltage,[5]

$$d(V_g+V_{gL})/dt<0 \quad \text{or} \quad V_g \sin\phi_g + nV_{gL}\sin\phi_{gL}>0 \qquad (14)$$

This implies that for the stability the vector sum $\tilde{V}_g + n\tilde{V}_{gL}$ should locate on the upper half plane of the diagram.

Meanwhile, the radiation energy of electron beam is compensated by accelerating RF voltage V_a,

$$U/e=V_a=V_g\cos\phi_g - V_b\cos\psi + V_{gL}\cos\phi_{gL} - V_{bL}\cos\psi_L \qquad (15)$$

Thus, for a given set of parameters, V_g, V_{gL}, V_b, V_{bL}, ψ and ψ_L, the phase diagram is uniquely determined by a free parameter ϕ_g or ϕ_{gL}. The cavity voltage V_c and V_{cL} are also determined uniquely by the relation $\tilde{V}_c=\tilde{V}_g+\tilde{V}_{gL}$ and $\tilde{V}_{cL}=\tilde{V}_{gL}+\tilde{V}_{bL}$. Then the stability of instability can be determined by substituting these parameters into inequlity (14), or by seeing whether the vector sum $\tilde{V}_g+2\tilde{V}_{gL}$ locates on the upper half plane.

Figure 5 represents a numerical example of the phase diagram at a beam current of 40 mA for the parameters given in the figure. The same numbers on the curves satisfy the equilibrium condition (15). The figure indicates that the states 2～8 are unstable because the vector sum $\tilde{V}_g+2\tilde{V}_{gL}$ locates on the lower half plane, while the states 1～2 and 9～10 are stable. If we put the beam bunch on the state 6, for instance, it moves toward the state 2 or 8 until it comes to a stable point indicated with closed circles. This accompanies simultaneus deformation of total voltage as shown in Fig.4. At a lower current the vector sum $\tilde{V}_g+2\tilde{V}_{gL}$ can be located on the upper half plane of the diagram, so that the phase slip does not occur. Above the threshold current the vector sum locates on the lower half plane and goes lower and lower as the beam current increases. Consequently, the Robinson instability becomes stronger and the phase feedback becomes harder.

In the above analysis we have assumed that the tuning angles ψ and ψ_L are negative to avoid the first kind Robinson instability. But we can safely make ψ_L positive; since the instability is induced by coherent interaction, it can be damped by Landau damping due to the large frequency spread produced by the double RF system. Figure 6 represents an example of the phase diagram for positive ψ_L. It shows that the beam bunch is stable even at a beam current of 160 mA. Further increase of the tuning angle increases the threshold current for the second kind instability up to 300 mA.

If we reduce V_{gL} to zero, or the Landau cavity is used as a passive cavity, the second kind instability can be stable at any beam current. But in this case the angle and magnitude of the cavity voltage V_{cL} $(=V_{bL})$ determined by the beam current are not necessariy optimum for Landau damping of the longitudinal instability. It is noted that positive detuning does not lengthen the beam bunch, but reduces it, which has been confirmed in BESSY.[6]

Conclusion

In the double RF system we can produce a very large spread in synchrotron frequency, which increases the threshold current of a coherent longitudinal instability. However, Robinson instability additionally induced limits the threshold current. The threshold current of Robinson instability can be increased considerably by selecting positive detuning in Landau cavity.

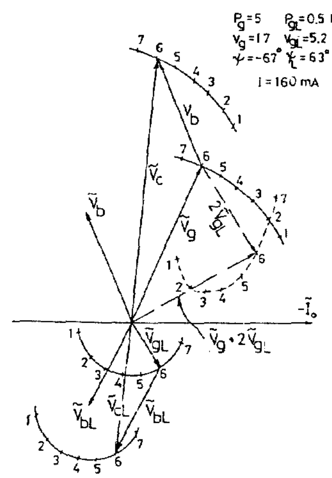

Fig.6 Phase diagram for positive detuning ψ_L in Landau cavity.

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