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Beam dynamics in super-conducting linear accelerator: Problems and solutions

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Abstract

The linac based on SC cavities has special features. Due to specific requirements the SC cavity is desirable to have a constant geometry of the accelerating cells with limited family number of cavities. All cavities are divided into modules, and each module is housed into one cryostat. First of all, such geometry of cavity leads to a non-synchronism. Secondly, the inter-cryostat drift space parametrically perturbs the longitudinal motion. In this article, we study the non-linear resonant effects due to the inter-cryostat drift space, using the separatrix formalism for a super-conducting linear accelerator [Yu. Senichev, A. Bogdanov, R. Maier, Phys. Rev. ST AB 6 (2003) 124001]. Methods to avoid or to compensate the resonant effect are also presented. We consider 3D beam dynamics together with space charge effects. The final lattice meets to all physical requirements.

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1. Introduction

Super-conducting (SC) RF technology allows getting the high gradient acceleration. Especially it is effective in case of low current, since the power required for the beam acceleration is much smaller than the RF power needed for the RF field creation in a normal-conducting cavity. Additional argument for a SC cavity is a possibility to accelerate particles with different charge-mass ratio due to independent feeding of cavities. However, due to lot of reasons a super-conducting cavity does not have flexible tuning as a normal-conducting cavity, and geometry of SC cavity has to be simplified as much as possible. In particular, it is desirable to have SC cavity with constant geometry of accelerating cells and changing from one family of cavities to another. It means the phase velocity changes step by step from family to family as well. The particles are sliding down or up relatively of RF wave in dependence on ratio between the particles and the wave velocities. Thus, the particles are almost never in synchronism with the equivalent traveling wave, and they have not instantaneous stability. Nevertheless, abandoning from synchronism, we acquire a freedom in choice of RF phase shift between relatively short SC cavities, which can provide the stable quasi-synchronous motion in whole accelerator.

For cryogenics all SC cavities are divided into modules, and each module is housed into one cryostat. However, some equipment, in particular, diagnostics, vacuum pumps and focusing elements desirable to place outside of cryostat under normal conditions. It requires an additional drift space between cryostats. The number of SC cavities in one module is determined by required length between focusing elements. In the same time drift spaces can be considered as a parametric perturbation of the longitudinal motion. Evident advantages of SC cavities initiate its application starting with the lowest possible energy. Moving down with energy the longitudinal frequency grows and it can be comparable with the repetition frequency of drift spaces. In this case, the resonance condition for particle in longitudinal plane can be realised. Since the drift space length can be comparable with the length of module, the resonance width can be significant and it could

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dramatically affect on beam stability. In this paper we study the resonant effects due to the inter-cryostat drift space. Developed theory let us follow the beam dynamics under the influence of different order parametric resonances, as well as estimate resonance width and find the most dangerous resonances. Methods to avoid or to compensate the resonant affect are also presented.

At present SC linear accelerator is considered as candidate for intensive beam with high duty cycle. We investigated the space charge effect in SC linear accelerator based on module lattice with long distance between focusing elements and strong defocusing RF field.

Due to absence of synchronous particle the SC linear accelerator has specificity in RF amplitude and phase tuning. In this article, we consider the modified delta-T procedure for SC linear accelerator.

All practical applications are considered on the example of COSY SC linac [2].

2. SC accelerators with stepped RF phase structure

We already mentioned that in SC linear accelerator the cavities are joint in families, and all n cavities of one family have the same structure phase velocity $\beta_{\rm str} = {\rm const}$ for $i \in 1-n$. Thus, particles move in a cavity, where the structure phase velocity $\beta_{\rm str}$ is constant. Therefore, they oscillate around $\varphi_s = 0^0$ (for "sin" wave). In the considered case the particle velocity deviation from the structure phase velocity $\Delta\beta = \beta_{\rm str} - \beta$ can exceeds the velocity spread of stationary separatrix with a synchronous level $\beta = \beta_{\rm str}$. Fig. 1 explains the mechanism of acceleration. It is based on an RF shift for each cavity. The particles have to return back each time after passing through a cavity to get an average phase $\overline{\phi_s}$ over all cavities. By a proper choice of the RF phase shift $\Delta\varphi_{\rm RF}$ between cavities one can create a

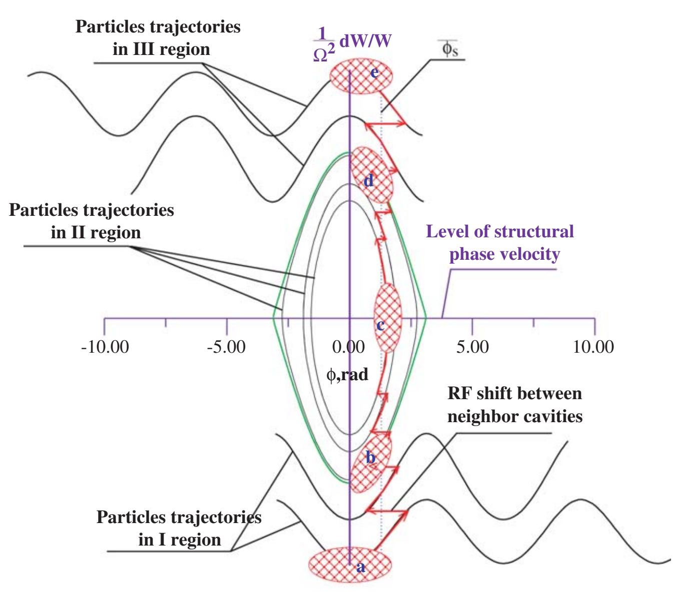

Fig. 1. Longitudinal motion in stepped RF phase structure.

quasi-synchronous motion and in total a stable motion in the whole accelerator. The quasi-synchronous particle oscillating in a cavity around $\varphi = 0^0$ is forced by the inter-cavity RF shift to oscillate around $\overline{\phi_s}$. In one cavity we can write the equations:

$$\frac{{\rm d}\phi}{{\rm d}\varsigma} = \frac{\beta_{\rm str}}{\beta} - 1$$
$$\frac{{\rm d}\beta}{{\rm d}\varsigma} = \frac{eE_{\rm ac}\lambda\beta_{\rm str}}{2\pi m_0 c^2\gamma^3\beta}\sin\phi \qquad (1)$$

where ${\rm d}\varsigma = 2\pi({\rm d}z/\beta_{\rm str}\lambda)$ is new normalized longitudinal coordinate, $E_{\rm ac}$ is accelerating field and λ is wave length. The separatrix in case of the stepped RF phase is created in the following way [1] . From Eq. (1) one derives the phase oscillation equation ${\rm d}^2\phi/{\rm d}\varsigma^2 + \Omega^2 \sin\phi = 0$, where $\Omega^2 = A_E \cdot \beta_{\rm str}^2/\beta^3$ is determined by means of parameter $A_E = eE_{\rm ac}\lambda/2\pi m_0 c^2\gamma^3$.

Obviously, if one does not undertake some action with phase ϕ, the particles will accelerate around phase $\phi = 0$, and acceleration will be absent, since $\Delta W \propto \overline{\sin\phi_s}$. To correct this situation, one adds the external phase shift $\varphi_{\rm str}(\varsigma)$ to the phase ϕ, and the corrected phase is:

$$\phi(\varsigma) = \int_0^{\varsigma} \frac{\beta_{\rm str}\,{\rm d}\xi}{\beta} - \int_0^{\varsigma} {\rm d}\xi + \varphi_{\rm str}(\varsigma) \qquad (2)$$

and the first equation of system (1) takes the form:

$$\frac{{\rm d}\phi}{{\rm d}\varsigma} = \frac{\beta_{\rm str}}{\beta} - 1 + \frac{{\rm d}\varphi_{\rm str}(\varsigma)}{{\rm d}\varsigma}. \qquad (3)$$

Then the phase oscillation equation is:

$$\frac{{\rm d}^2\phi}{{\rm d}\varsigma^2} + \Omega^2 \sin\phi - \frac{{\rm d}^2\varphi_{\rm str}}{{\rm d}\varsigma^2} = 0. \qquad (4)$$

Thus, the second derivative of $\varphi_{\rm str}(\varsigma)$ defines the acceleration rate in the stepped RF phase structure.

However, the RF phase of each cavity is fixed and changes from cavity to cavity step by step. The step value is proportional to periodicity T of the cavities. It is a stepwise function with an average value $\overline{\varphi}_{\rm str}$ coinciding with an RF shift of the ideal case. Introducing a "triangular" function $\tilde{\varphi}_{norm} = \sum_{m=1}^{\infty}(1/\pi m)\sin m\nu_{\rm ph}\varsigma$, the real $\varphi_{\rm str}(\varsigma)$ could be submitted through the sum:

$$\varphi_{\rm str}(\varsigma) = \overline{\varphi}_{\rm str}(\varsigma) + \frac{{\rm d}\overline{\varphi}_{\rm str}}{{\rm d}\varsigma} \cdot 2\pi \cdot T \cdot \tilde{\varphi}_{norm}(\varsigma). \qquad (5)$$

As distinct from the stepped phase velocity structure in the considered structure the amplitude of triangular function is proportional to the derivative $({\rm d}\overline{\varphi}_{\rm str}/{\rm d}\varsigma) \cdot 2\pi \cdot T$:

$$\tilde{\varphi}_{\rm str} = \frac{{\rm d}\overline{\varphi}_{\rm str}}{{\rm d}\varsigma} \cdot 2\pi \cdot T \cdot \sum_{m=1}^{\infty} \frac{1}{\pi m} \sin m\nu_{\rm ph}\varsigma \qquad (6)$$