APPLICATION OF ELECTROSTATIC UNDULATORS FOR ACCELERATION OF INTENSE ION BEAMS

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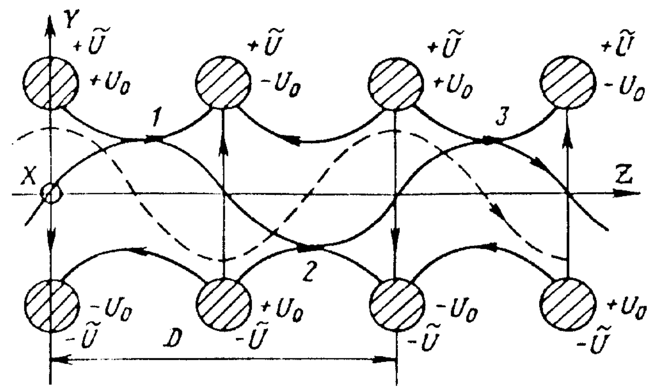
Some questions of ion beams interaction with RF and electrostatic fields in a linear undulator accelerator (lineondutron) with the plane undulator are considered. It is shown that in a lineondutron simultaneous acceleration of oppositely charged particles with the identical charge-to-mass ratio(for ex, $H^+$and H^-) may essentially increase the overall beam intensity up to a few Amp.

1. INTRODUCTION

An idea to apply undulators for acceleration of relativistic beams in a plane electromagnetic wave was discussed more than once. Various mechanisms and acceleration schemes were proposed to accelerate electrons in magnetostatic undulators and their description can be found in Refs.[1-3]. The similar principles can also be used for acceleration of non-relativistic ion beams [4]. In this case for low injection energy it is advisable to replace the magnetostatic undulator by the electrostatic one. The configuration of periodic electrostatic field can be chosen so as to provide an effective transverse particle focusing without applying additional external fields [5].

In this paper we discuss one of the possible versions of such linear accelerator, in which the ribbon ion beam is accelerated in the transverse RF- field and the field of a plane electrostatic undulator. The required field distribution is achieved by the appropriate system of electrodes, mounted in a resonator and dc-isolated between each other. Both the RF- and electrostatic potentials are supplied to adjacent electrodes, forming the accelerating channel (indicated by $\tilde{U}$ and U_0 in fig.)



The RF-frequency corresponds to the undulator space period D. Once influenced only by the RF or electrostatic field , the particle travels along the dotted curve in fig., and, as it is evident, its energy remains constant. If both the fields simultaneously influence on the charge, the particle energy doesn't vary in the transverse direction and increases in the longitudinal direction. The corresponding electrostatic field lines and particle trajectory in a combined-wave field are indicated in fig. by the solid line.

2. PARTICLE MOTION EQUATIONS

In a lineondutron scheme proposed a plane electrostatic undulator is combined with the RF-system. The electrode positions define the values of the fundamental space harmonics: the zero RF-field harmonic and the first electrostatic field harmonic, which are the working ones in our case. Higher harmonics values , in turn, depend greately on the electrode shape and size.

The field strengthes in the periodic system involved can be represented as

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$$a_y^v=a_v\left(1+\sum_{n=1}^{\infty}\text{æ}_{2n}\,ch2kny\,\cos\left(2n\int_0^z kdz\right)\sin(\tau+\tau_0)\right),$$

$$a_z^v=-a_v\sum_{n=1}^{\infty}\text{æ}_{2n}\,sh2kny\,\sin\left(2n\int_0^z kdz\right)\sin(\tau+\tau_0)\ ,$$

$$a_y^o=a_o\sum_{m=1}^{\infty}g_{2m-1}\,ch(2m-1)ky\,\cos(2m-1)\int_0^z kdz, \qquad (1)$$

$$a_z^o=-a_o\sum_{m=1}^{\infty}g_{2m-1}\,sh(2m-1)ky\,\sin(2m-1)\int_0^z kdz,$$

where $a_v= eE_v\lambda/2\pi mc^2$ and $a_o= eE_o\lambda/2\pi mc^2$ - the dimensionless amplitudes of the zero RF-field harmonic and the 1-st electrostatic field harmonic, λ-the RF-field wavelength, $\beta_s=D/\lambda$-the synchronous particle velocity, $\tau=2\pi ct/\lambda$, $\text{æ}_{2n}(n\geq1)$, $g_{2m-1}(m\geq2)$-the normalized higher harmonics amplitudes, which, as well as the fundamental ones, are non-syncronous with the beam, $k=2\pi/D(z)$ - the wavenumber.

By using the smooth approximation method one may derive the expression for the effective potential, describing the averaged particle motion

$$U_{eff}=U_o+\Delta U, \qquad (2)$$

where $U_o=a_o^2 ch(2\rho/\beta_s)/4 - a_v a_o ch(\rho/\beta_s)/2 + a_v^2/4$ the potential due to fundamental harmonics, ΔU -an addition due to the higher harmonics, $\varphi=\int_0^\xi d\xi/\beta_s-\tau+\tau_o$- the slow varying fase in a combined-wave field, $\xi=2\pi Z/\lambda$ and $\rho=2\pi Y/\lambda$- the normalized longitudinal and transverse coordinates in the smooth approximation.

Correspondingly, the averaged motion equations can be written as

$$\frac{d^2\xi}{d\tau^2}=-\frac{\partial U_{eff}}{\partial\xi}\ ;\quad \frac{d^2\rho}{d\tau^2}=-\frac{\partial U_{eff}}{\partial\rho} \qquad (3)$$

3. FASE AND TRANSVERSE STABILITY CONDITIONS

Considering the higher harmonics, we may restrict ourselves by the harmonics, nearest to the working ones. Then near the injection plane (ρ =0) the first eq. (3) yields:

$$\frac{d\beta_z}{d\tau}=\frac{b_o^2}{2\beta_s}(1+\Delta)\cos\varphi, \qquad (4)$$

where $b_o^2=a_o\ a_v$, $\alpha = a_v/a_o$, $\Delta= \text{æ}_2/2 + \text{æ}_2\ g_3/18- 2\ \alpha\ \text{æ}_2 \sin\varphi$. When neglecting the higher harmonics, the acceleration rate is proportional to $a_o\ a_v$. An appropriate choice of the functions $a_o(\xi)$, $a_v(\xi)$ and $\varphi_s(\xi)$ turns out to supply an effective bunching and acceleration of the beam. If $\Delta=0$ and $\rho = 0$, the potential function has the only minimum at the point $\varphi=\varphi_s$. When æ_2 increases, the syncronous particle energy decreases, as a rule. At the same time the phase and momentum stability region grows. With the further increase of æ_2 the second minimum of U_{eff}, as well as the second separatrix appear. In that case the minimum at $\varphi=\varphi_s$ becomes less pronounced and gradually disappears.

From eq.(3) one may obtain the condition of the transverse particle focusing. Taking into account the fundamental harmonics, we get

$$2\ ch\ (2\rho/\beta_s)\geq\alpha\ ch\ (\rho/\beta_s)\sin\varphi. \qquad (5)$$

When $\alpha\sin\varphi < 2$ for the particle fase φ $U_{eff}(\rho)$ has one minimum at $\rho=0$. If $\alpha\sin\varphi > 2$, an intermediate maximum at $\rho=0$ appears, and at $\rho = \pm\rho_o$, where ρ_o is a root of the equation $ch\ (\rho/\beta_s)= \alpha\sin\varphi/2$, two minimums take place. Thus, two stable trajectories of the beam, splitted spatially and located outside the plane $\rho=0$, appear. The particle, depending on its initial conditions, can be placed on one of such trajectories, and the beam - splitted into two beams, what is undesirable.

Taking into account the effect of the higher harmonics on the transverse beam dynamics doesn't change significantly the qualitative picture, described above. However, the stability conditions are defined from more complication equation. The analysis of the expression for ΔU showed, that with the increase of $æ_2$ the transverse oscillation frequency ω_Y decreases, and the focusing is worsed. Inversely, at $g_3 < 0$ with the increased $|g_3|$ ω_Y grows.

4. ACCELERATION OF QUASI - NEUTRAL BEAMS

All the results, obtained above, relate to acceleration of both the positive and negative ions. An interesting property of a lineondutron is that it doesn't distinguish between them. The acceleration equations are independent of the sign of charges. Therefore, under the identical ratio ($Z^{\pm}$/ M)(for ex., H^+ and H^-)and the same injection conditions bunching and capture processes occur at the same resonant fase. This can allow accelerating overlapping positevely and negatively charged ion bunches , thus avoiding space-charged effects and increasing overall beam intensity. Such bunches can be made practically neutral.

The dynamics of intense beams, including space-charge effects , can be analyzed in more detail only by means of exact numerical integration studies. Numerical results confirm the conclusions, made before analytically. For the quasi-neutral bunches the results, obtained in a single- charge approximation, are found to be close enough to those obtained while taking into account intrinsic quasi-static beam fields. It takes place , even if the trajectories of the oppositely charged particles don't completely overlapp in the transverse cross-section.

The corresponding choice of the fundamentaland higher field harmonics enables to provide the focusing of quasi-neutral bunches in that case, if it exists for a single particle. The electrodes may have circular or rectangular profile. Calculations show that under the geometrical sizes of electrodes, normally used in practice, the harmonic amplitudes range as follows: $æ_2$=0÷0.2, g_3= -0.3 ÷ 0.3.

5. CONCLUSION

Simulation results of the beam dynamics and detailed study of forming the requred fields showed, that it is possible to create a lineondutron with a final energy of about 1 Mev. For example ,the parameters of $H^+$and H^-accelerator with an injection energy of 50 kev, RF- generator frequency of 150 MHz were calculated. The accelerator includes bunching and acceleration sections. On the former the field amplitudes gradually increase, and the syncronous fase decreases by the linear law. On the latter these dependencies are chosen constant. The main accelerator characteristics are the following: average acceleration rate - 0.55 Mev/m; capture coefficient- 0.8; transversal acceptance ≃ 0.1 cm.mrad; RF- and electrostatic field amplitudes - 180 kV/cm and 65 kV/cm respectively; minimum half-size of the ribbon aperture - about 4 mm.

6. REFERENCES

[1] A.A.Kolomensky and A.N.Lebedev, "Quasilinear acceleration of particles by a transverse electromagnetic wave", Zh. Eksp.Teor.Fiz, vol.50,pp.1099-1106,1966.

[2] R.B. Palmer,"Interaction of relativistic particles with free electromagnetic waves in the presence of a static helical magnet", J.Appl.Phys.,vol.50, pp. 3014-3023,1972.

[3] E.D. Courant, C. Pelligrini and W.Zakowicz,"High energy inverse free-electron laser accelerator",Phys.Rev.A, vol.32, pp.2813-2823, Nov.1985.

[4] E.S. Masunov,"Beam focusing and acceleration in a linear accelerator acceleratior",in USSR Conference On Charged Particle Accelerators Proc.,Dubna,USSR, Oct.1988,pp.121-123.

[5] E.S. Masunov,"Particle dynamics in a linear undulator accelerator",Zh.Tekn. Fiz,vol.60, 8, pp.152-157,1990.