Acceleration and Transverse Focusing of Ion Beams in Lineondutron

Edward S. Masunov, Moscow Engineering Physics Institute, 115409, Moscow, Russia

Abstract

The main features of beam dynamics in linear accelerator with magnetostatic undulators (lineondutron) are discussed. Some expressions correlating the amplitude value of undulator and RF-fields under which the focusing and acceleration of particles take place in the absence of synchronism with the harmonics of RF-field are found. The configuration of magnetostatic and RF-field can be chosen to provide an effective bunching and acceleration of the beam.

I. INTRODUCTION

The idea to apply a combination of electrostatic field of undulator and radiofrequency field for acceleration and focusing of intense ion beams with low injection energy was discussed in [1], [2]. Employment of electrostatic undulator is useful for small values of initial particle velocity. The magnetostatic undulator may substitute instead of electrostatic one in case of high injection energy (W>100 keV for proton beams).

In this paper we shall discuss the main features of beam dynamics in a lineondutron with magnetostatic undulator. In the evaluation of beam bunching and acceleration processes it is important to take into account the beam defocusing in a combined wave-undulator field. The motion equation of the particle may be written, using Lagrange function:

$$\frac{d}{dt}\vec{P} = e\vec{\nabla}(\vec{v}\cdot\vec{A} - \Phi), \tag{1}$$

where $\vec{P} = \vec{p} + e\vec{A}$ -- generalized momentum of particle, $\vec{A} = \vec{A}_v + \vec{A}_0$ -- the overall potential vector of RF-field and periodical magnetostatic field, Φ -- potential of electrostatic field.

II. LONGITUDINAL BEAM DYNAMICS

Let us see the beam dynamics in the magnetostatic undulator (Φ=0) in the case, when no RF-field harmonics are synchronized with the beam. The trajectories of single beam particles in general case have complex nature, but they may always be represented as a combination of fast oscillations $\tilde{\vec{r}}(t)$ and slow variation $\vec{R}_c(t)$. Correspondingly, kinetic momentum of particle $\vec{p}$ is represented as a sum of slowly varying and quickly oscillating components $\vec{p} = \vec{p}_c + \tilde{\vec{p}}$. By averaging over quick oscillations, from (1) we obtain an equation, which describes the slow evolution $\vec{R}_c$

$$\frac{d}{dt}\vec{R}_c = -\frac{e^2}{2m\gamma}\vec{\nabla}\left\langle\left(\vec{A}_v + \vec{A}_0\right)^2\right\rangle, \tag{2}$$

Taking into account only the fundamental space harmonics of the wave and undulator, the equation (2) can be rewritten in the form

$$\frac{d}{dt}\left(\gamma_c\vec{\beta}_c\right) = -\frac{\lambda}{8\pi\gamma_s}\vec{\nabla}U, \tag{3}$$

where the potential function

$$U = \vec{b}_v^2 + \vec{b}_0^2 - 2\vec{b}_v\cdot\vec{b}_0\sin\psi. \tag{4}$$

Here $\vec{b}_{v,0} = e\vec{B}^{\perp}_{v,0}\lambda_{v,0}/2\pi mc$ -- the dimensionless amplitudes of the transverse components of the wave magnetic field $\vec{B}_v$ and the undulator field $\vec{B}_0$, $\vec{B}_{v,0} = \mathrm{rot}\,\vec{A}_{v,0}$, $\psi = \omega\int dz/v_s - \tau + \psi_0$ -- the particle phase in a combined wave field, ω -- the frequency of RF-field, $\tau=\omega t$, ψ_0 -- the initial phase.

The normalized velocity of a synchronized wave is

$$\beta_s^{\pm} = \frac{v_s^{\pm}}{c} = \frac{\beta_v\lambda_0}{\lambda_0 \pm \beta_v\lambda_v}, \tag{5}$$

where β_v and λ_v -- the normalized phase velocity and RF-field wavelength, λ_0 -- the undulator period.

From (3) one can see that the longitudinal bunching and acceleration of the beam are possible even in the field of TE- or TEM-wave as a result of joint influence on the beam of non-synchronized RF- and undulator fields harmonics. The beam energy is increased due to RF-field energy.

At the given amplitudes the energy increase $\Delta\gamma = \Delta W/mc^2$ on the length λ_0 will be maximum, when the transverse symmetry (antisymmetry) planes over the magnetic field of the RF-wave and undulator coincide with the plane, along which the beam is injected. In this case for a synchronized particle

$$\Delta\gamma = \frac{\pi\lambda_0}{\beta_s\lambda\gamma_c}b_v b_0\cos\psi_s, \tag{6}$$

i.e. the acceleration rate is proportional to the amplitudes of RF- and undulator fields.

High level capture and good bunching of the beam may be obtained, provided one supplied the adiabatic growth of the values $b_v(z)$ and $b_0(z)$ along the longitudinal axis and corresponding increase of the undulator period λ_0, to maintain the beam synchronism with a combined wave field.

0-7803-1203-1/93$03.00 © 1993 IEEE

III. TRANSVERSE FOCUSING OF BEAM

The choice of the functions $b_\upsilon(z)$ and $b_0(z)$ is not arbitrary because simultaneously with acceleration it is necessary to supply transverse focusing of the beam. Let us note that magnetostatic undulator with transverse deflection fields can always be treated as a device producing slalom beam focusing. The transverse RF-field of the wave can both focus and defocus the beam. A combined wave and undulator field, accelerating particles in the longitudinal direction, defocuses them in the transverse direction. Finally, the sum effect may be found only from the analysis of equation solutions (3). As one can see from (3) and (4), equilibrious trajectory may exist for all the particles of the injected beam, if two conditions for the injection plane are valid,

$$\vec{\nabla}_\perp(\vec{b}_\upsilon^2 + \vec{b}_0^2) = 0 \text{ and } \vec{\nabla}_\perp(\vec{b}_\upsilon \cdot \vec{b}_0) = 0. \qquad (7)$$

In the simplest case, when the axis of magnetic undulator coincides with that of RF-system and the beam is injected along it, equalities (7) are validated automatically. In other cases an equilibrious trajectory exists, if the field amplitudes and their transverse gradients are connected by the relations

$$B_0 = \frac{\lambda_\upsilon}{\lambda_0} B_\upsilon, \quad \vec{\nabla}_\perp B_0 = -\frac{\lambda_\upsilon}{\lambda_0} \vec{\nabla}_\perp B_\upsilon. \qquad (8)$$

This result may be used at high value of the aperture of the accelerating channel, because it allows to inject particles beyond the axis, closing the beam to the poles of undulators, in order to increase the efficiency of acceleration. Moreover, if the RF-field and undulator field have multiple symmetry (antisymmetry) planes, one can simultaneously accelerate several beams.

The condition of the transverse particle focusing may be obtained from (4), when the effective potential U_{eff} has the minimum. If the beam is injected on the axis, a focusing takes place for all particle phases, when

$$B_\upsilon < \alpha \frac{\lambda_0}{\lambda_\upsilon} B_0, \qquad (9)$$

where $\alpha \simeq 1$ and depends on field structure and beam phase size.

At low energy of injection in lineondutron the amplitude of the undulator field B_0 will be high because $\beta_s = \lambda_0/\lambda_\upsilon << 1$. The value B_0 may be decreased, if additional electrostatic field $\vec{E}_c^\perp = -\vec{\nabla}_\perp \Phi(\vec{r}^\perp)$ is used. The equilibrious trajectory may exist for all particles of beam, when

$$\vec{\nabla}_\perp(\vec{B}_\upsilon^\perp \cdot \vec{B}_0^\perp) = 0 \qquad (10)$$

and

$$\vec{E}_c^\perp = \frac{e\lambda_\upsilon^2}{8\pi m\gamma}\left(1 - \frac{\lambda_\upsilon^2 \vec{B}_\upsilon^{\perp 2}}{\lambda_0^2 \vec{B}_0^{\perp 2}}\right)\vec{\nabla}_\perp \vec{B}_0^{\perp 2}. \qquad (11)$$

IV. SOME EXAMPLES

The effective amplitude of the accelerating field $E_{eff} = T_B E_\upsilon$, where E_υ is amplitude of RF-field, T_B is a parameter, proportional to the amplitude of undulator field,

$$T_B = \frac{eB_0\lambda_0}{4\pi mc\beta_s\gamma_c}.$$

For bunching and acceleration of nonrelativistic protons it is convenient to use RF-resonators, based on uniform longitudinal oscillators. When $\lambda_\upsilon = 3$ m, $\lambda_0 = 0.045$ m, we have β_s=1.5 · 10^{-2}, that corresponds to injection energy W_i=100 keV. If B_0= 2 T then E_υ = 90 kV/cm and maximal increase of energy in such an accelerator: 1.4 MeV/m. The value E_υ may be increased two times without variation of the acceleration rate, provided one decreases B_0 up to 1 T and introduces an additional transverse electrostatic field, value of which is not greater than E_c ~ 20 – 30 kV/cm.

V. CONCLUSION

Use of magnetostatic undulators to accelerate and to focus ion beams promises to be a very perspective practice. The necessity to use slowing-down systems is removed. RF-systems may by uniform ones that facilitates their tuning. By means of variation in the amplitude and in the period of the undulator field, there is a chance to provide high level capture factor of the beam and its effective bunching. Big opportunities are opened by applying lineondutron to accelerate quasi-neutral beams constituted by particles with the same *Z/M* ratio but with opposite signs of charge (for example, H^+ and H^-). Positively and negatively charged particles are accelerated in the same bunch. Therefore, when injecting quasi-neutral beam into such an accelerator, no difficulties arise related to limiting intensity due to the value of space charge.

VI. REFERENCES

[1] E. Masunov, A. Novicov, "Application of electrostatic undulator for acceleration of intense ion beams", *Conference Record of the 1991 IEEE Particle Accelerator Conference,* Vol. 5, pp. 3177--3179.

[2] E. Masunov, V. Leonov et. al., "A project of ion linear undulator accelerator with transverse RF-field", *Proceedings of the Third European Particle Accelerator Conference,* 1992, Vol. 1, pp. 572--574.