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BEAM BREAKUP IN A MULTI-SECTIONAL ION LINAC

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Summary

The instability of a high-intensity beam caused by the electromagnetic transverse components in a multi-sectional ion linac is considered. For the case of steady state single-mode beam cavity interaction an analytical estimate of the limiting current is obtained. Simulation of transverse beam-cavity interaction has been performed for the DAW structure of the INR meson factory linac. It is shown that the DAW structure used in the main part of the INR linac the e-fold factor is equal to unity at a beam current level of about 350 mA. The dispersion relation and the transverse shunt-impedance estimate were calculated by using computer code PRUD.

Introduction

It is known (see, for example, ref 1) that the beam current of the electron linac is limited by the beam break up instability. In a multi-sectional accelerator with a long beam pulse duration this effect is very dangerous. Similar instability mechanism can occur in a proton linac. The estimates carried for a single section proton linac[2] had showed that the limiting current due to the beam breakup is sufficiently large and essentially exceeds the space charge limit value. However, the situation becomes more complicated in the multi sectional proton accelerators. In this case the small transverse displacement of the beam in a single section arising under the beam induced hybride wave can be accumulated and result in significant effect.

The rise of the beam transverse displacement can be rather strong for the high-intensity linac or the meson factory type. Such a linac assigned to accelerate the high-intensity H^+ and H^- beams up to 600-800 MeV, is a few hundred meters long and consists of a large number of the accelerating sections[3]. The results of the analytical calculation and numerical simulation of the transverse instability in a multi-sectional proton linac are given below. As an example the beam break up limit for the INR meson factory linac[4,5] is considered. The feature of this linac is that the dispersion diagram of the disk and washer (DAW) accelerating structure is very tight: a large number of the HE_{11} modes with a sufficiently large transverse shunt-impedance $r_\perp$ and the quality factor Q are disposed not so far from the main branch of the dispersion curve[6].

An analytical steady-state solution

Considering the instability mechanism we assume that the accelerator consists of a large number accelerating sections of the length L_s. The beam is presented as a chain of the bunches moving along the linac with a constant energy gain and following one after another in equal interval. For simplicity, we assume that the beam does not change its position within the section and a frequency of the hybrid mode is the same in all sections. If the bunch excites the hybrid mode in some section it will affect other bunches resulting in their transverse displacement. Each following bunch feels a total field radiated by the preceding bunches and therefore receives a larger deflection. As a result the hybrid wave excited by it will have a larger amplitude. Thus the transverse coordinate gets larger as soon as the number of the bunch and longitudinal coordinate Z grow.

To analyse the beam instability we take into account just a single HE_{11}-mode (with one azimuthal variation). The Lorentz force acting on a particle moving in such wave is constant and a field amplitude E_o is proportional to the beam deflection from the axis. It could be shown that in a steady-state conditions ($\tau_i \omega / 2Q \gg 1$, where τ_i is the pulse duration):

$$E_o = \frac{k_1 I r_\perp}{2 L_s} \mathrm{Re} \left\{ \int x(z,\tau) e^{-i(\omega_1 \tau - \Delta(z))} dz \right\} \quad (1)$$

where $\Delta(z) = k_1 \int_0^z \left(\frac{1}{\beta} - \frac{1}{\beta_s} \right) dz'$, $k_1 = \frac{\omega_1}{c}$

is the wavenumber, βc is the phase velocity of the hybrid wave, I is the pulsed beam current.

Let us present $x(z,\tau)$ in the form $x(z,\tau) = x_o(z)\, e^{i\omega\tau}$. Under assumptions taken above the self-consistent equation for the complex amplitude $x_o(z)$ of the transverse bunch displacement is given by

$$\frac{d}{dz}\left(\beta_s \gamma_s \frac{dx_o}{dz}\right) + K^2 x_o + iG x_o = 0 , \quad (2)$$

where $K = \frac{\mu_o \beta_{si} \gamma_{si}}{\ell_{f1} \sqrt{\beta_s \gamma_s}}$ is the wave number of the transverse particle oscillations depending on the rigidity of the quadrupole focusing, μ_o is the phase shift of the transverse oscillations per period, ℓ_{f1} is the length of the first focusing period

$$G = \frac{e}{m_o c^2} \frac{k_1 I r_\perp L_s}{2 \ell_f} , \quad \ell_f$$

is the length of the current focusing period proportional to $\beta_s \gamma_s$; e, m_o are charge and mass of proton, γ_s is the Lorentz factor. Solution of the equation (2) has been obtained by the Laplace transformation. It shows that $/x_o/$ grows exponentially with the exponent

$$\alpha = \int_0^z \frac{G(z')\, dz'}{2K(z') \sqrt{\beta_s \gamma_s}}$$

If one supposes that the amplitude is permited to be grown e times ($\alpha = 1$) then formula (3) for the estimate of the "limiting" current in a multi-sectional proton linac of the length L could be obtained:

$$I_\ell = 2 \frac{m_o c^2}{e} \frac{\mu_o \lambda_1}{\pi r_\perp L_{si} L} \frac{\gamma_{se} - \gamma_{si}}{(\beta_s \gamma_s)_e - (\beta_s \gamma_s)_i} . \quad (3)$$

The subcripts i and e correspond to the entrance and exit of the linac. In accordance with expression (3) the limiting current for INR meson factory linac ($r_\perp \simeq 2$ MΩ/m) is equal to ~150 mA (Fig.1)

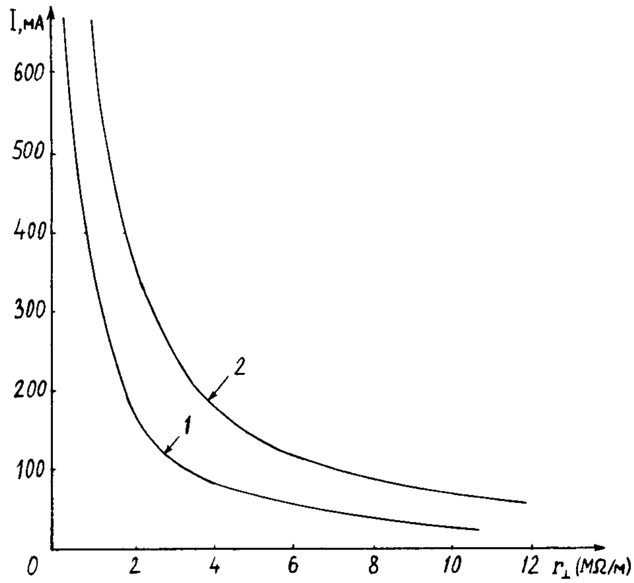

Fig.1 Limiting current as a function of the transverse shunt-impedance of the HE_{11} wave for the INR meson factory linac (1 - analytical calculation, 2 - computer simulation).

Computer simulation

To take into account the concrete accelerating and focusing structure of the proton linac as well as the phase sliding of the bunch relatively the HE_{11} wave the computer simulation of the beam interaction with the hybrid waves for the INR meson factory linac was carried out. The self-consistent equation for the complex amplitude of the transverse displacement was written in the form:

$$\frac{d^2x_0}{dz^2} = \frac{1}{\beta_s\gamma_s}\left[-\frac{d(\beta_s\gamma_s)}{dz}\frac{dx_0}{dz} - h_1\Omega_f^2 x_0 + h_2\Omega_d^2 x_0 - -iG_1 \cdot e^{-i\Delta(z)} Re\left(\int_0^{L_s} x_0 e^{i\Delta(z')} dz'\right)\right] \quad (4)$$

where

$$h_1(z) = \begin{cases} 1 & \text{in a focusing lens} \\ -1 & \text{in a defocusing lens} \\ 0 & \text{in another space,} \end{cases}$$

$$h_2(z) = \begin{cases} 1 & \text{in an accelerating section} \\ 0 & \text{in another space} \end{cases}$$

$\Omega_f^2 = \frac{eB'}{m_0 c}$, B' is the magnetic field gradient

$\Omega_d^2 = \frac{eE \sin\varphi_s}{m_0 c^2 \beta_s^2 \gamma_s^2 \lambda_0}$, λ_0 is the accelerating field wave length, E is the amplitude of the equivalent accelerating travelling wave, φ_s is the synchronous phase, $G_1 = \frac{e}{m_0 c^2}\frac{2\pi r_\perp I}{L_s \lambda_1}$.

In each section the equation (4) has been solved for the fixed energy gain until converging value of the integral

$$Re\left\{\int_0^{L_s} x_0 e^{-i\Delta(z')} dz'\right\}$$

was obtained. The growth of the transverse beam displacements $/x_0/$ along the accelerator for different values $G_0 = \pi e r_\perp I/m_0 c^2$ [M^{-1}] is shown in Fig.2.

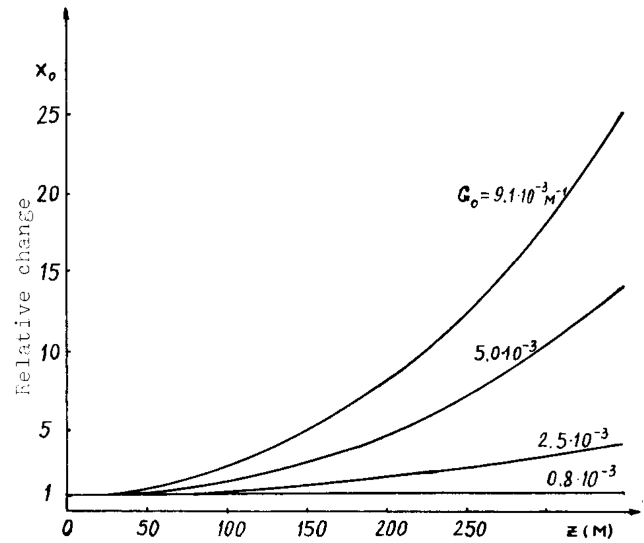

Fig.2. The growth of the transverse beam displacement in the INR meson factory linac due to beam breakup instability.

The limiting current I_ℓ is presented as a function of the transverse shunt-impedance by curve 2 in Fig.1.

The numerical estimate of the transverse shunt-impedance $r_\perp$ for the DAW accelerating structure were calculated by using the PRUD-code[7]. In accordance with this estimate $r_\perp = 2$ MΩ/M in the first sections of the main part of the INR meson factory linac, which corresponds to the limiting current about 350 mA (Fig.1).

Conclusions

Thus the examination given above showes that the beam break up instability in a linac of the meson factory type is not extremely dangerous. However, it should be taken into account very seriously for the proton linacs of next generation assigned to the electronuclear breeding or to be used as a high-intensity neutron generators. In this case the beam emittance growth should be carefully calculated taking into account the change of the dispersion curve of the hybrid modes from the section to section.

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