RF RIBBON BEAM ACCELERATOR FOR HEATING THERMONUCLEAR PLASMAS

V.D.Danilov, A.A.Iliin, Y.K.Batygin

Electrophysics Department
Moscow Engineering Physics Institute, 115409, Moscow, Russia

Abstract

Rf ribbon beam accelerator concept is presented. The transverse RF field focusing principle used in accelerator is discussed. The main considerations concerning the design of accelerating structure are given. The proposal on 150 MHz RF ribbon beam H^- accelerator with input energy 0.1 MeV, output energy 2 MeV and beam current 1 A for heating thermonuclear plasmas is presented.

Introduction

Injection of fast hydrogen (deuterium) atoms is an effective way to heat thermonuclear plasmas. The injector for such applications must provide neutralized beams with energy 1...2 MeV and total beam power 80...100 MW. High power H^- accelerating system can be constructed as a combination of RF ribbon beam linacs with the funneling and stripping systems. Such combination has the following features:

- high value of beam current using large width of the beam,
- large surface for effective beam neutralization,
- convenient beam funneling for limited injection region,
- suitable combination with high current ion sources with large slots for ion extraction.

A few aspects of RF ribbon beam accelerator design are discussed below.

Ribbon Beam Dynamics

Ribbon beam can be accelerated in a structure based on an interdigital H-resonator. We restrict our consideration to 2D beam dynamics investigation in accelerating channel formed by a sequence of long electrodes (see fig. 1). The problem is assumed to be x-uniform. Suppose the beam interacts with two distinguished space harmonics of electromagnetic field with amplitudes E_s , E_f , phases θ_s , θ_f and wave numbers K_s , K_f :

$$E_z = E_s\, ch(K_s y)\cos(K_s z - \omega_0 t + \theta_s) + E_f\, ch(K_f y)\cos(K_f z - \omega_0 t + \theta_f), \quad (1)$$

$$E_y = E_s\, sh(K_s y)\sin(K_s z - \omega_0 t + \theta_s) + E_f\, sh(K_f y)\sin(K_f z - \omega_0 t + \theta_f).$$

The acceleration of the particles is provided by a harmonic E_s with phase velocity closed to the average velocity of the particles (syncronous harmonic) and sign-alternating focusing of particles is provided by a nonsyncronous harmonic E_f . The appropriate spectrum of RF field for simultaneous acceleration and focusing of particles is achieved by adjusting the shape and distribution of electrodes along the channel.

RF acceleration theory for an axial-symmetric beam using nonsyncronous harmonics for the focusing of the particles has been developed in a series of publications [1-4] . The proof-of-principle was given with RF proton accelerator "URAGAN-2" for energy 0.5 MeV in 1988 [5] . Here the results of the previous considerations are generalized to the case of the ribbon beam accelerator.

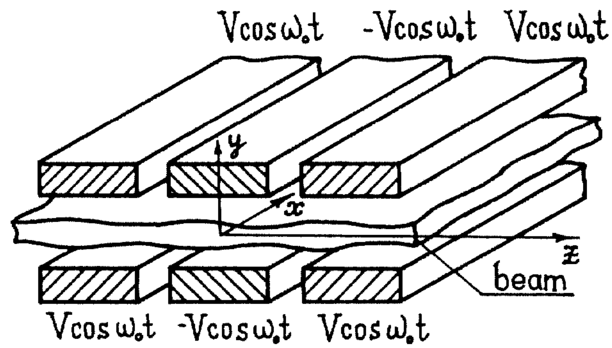

Fig. 1. Schematic representation of RF accelerating channel with a ribbon beam.

Phase Oscillations

The smooth approximation to the phase oscillations of the particle in a combination of two harmonics gives the phase stability equation:

$$\frac{d^2\bar{\varphi}}{d\tau^2} = A_s[ch(\bar{\eta})\cos(\bar{\varphi}+\bar{\varphi}_s) - \cos\bar{\varphi}_s], \quad (2)$$

where $\bar{\varphi} = K_s(\bar{z}-\bar{z}_s)$; $\bar{\eta} = K_s\bar{y}$ are averaged normalised longitudinal and transversal deviation from syncronous particle, $\tau = \omega_0 t$ dimensionless time, $\bar{\varphi}_s$ averaged value of syncronous phase, $A_s = eE_s\lambda/(2\pi E_0\beta_s)$ normalised amplitude of syncronous harmonic, λ wavelength, e charge, E_0 rest energy of the particle, $\beta_s = v_s/c$ reduced velocity of syncronous particle. Syncronous harmonic of RF field provides phasing and acceleration of the particles if $0 < \bar{\varphi}_s < \pi/2$. The energy gain of syncronous particle is $dW_s/dz = E_s\cos\bar{\varphi}_s$ and longitudinal oscillations frequency $\Omega_z/\omega_0 = (A_s\sin\bar{\varphi}_s)^{1/2}$.

The value of longitudinal limited beam current I_z is obtained using elliptic approximation of bunch with semi-axises $Z_s/2$, $Y_s/2$:

$$I_z = \frac{\pi I_0}{Z_s}\left(\frac{Z_s}{\lambda}\right)^3\left(\frac{\Omega_z}{\omega_0}\right)^2\left(1+\frac{Y_s}{Z_s}\right), \quad (3)$$

where $I_0 = 4\pi\varepsilon_0 m_0 c^3/e$ is a characteristic value of beam current. Effective bunch length Z_s is defined by parabolic approximation of longitudinal potential function.

One of the problem connected with RF field spectrum design is a possible overlapping of syncronous resonance with another one on the phase plane. It means that the longitudinal motion stability must be guaranteed against pertubation of the focusing component of RF field.

Transversal Oscillations

The averaged value of transversal oscillations frequency Ω_y is:

$$\frac{\Omega_y}{\omega_0} = \left[-A_s \sin(\bar{\varphi}+\bar{\varphi}_s) + \left(\frac{A_f G}{1-G}\right)^2\right]^{1/2}, \tag{4}$$

where $A_f = eE_f\lambda/(2\pi E_0\beta_s)$ is a normalised amplitude of focusing harmonic, $G = K_f/K_s$ is a ratio of wave numbers. The focusing effect depend on the amplitude of nonsyncronous harmonic and the frequency of focusing field $\omega_0|1-G|$. The value of phase shift per period of focusing μ is

$$\mu(\bar{\varphi}) = 2\pi\,\frac{\Omega_y(\bar{\varphi})}{\omega_0|1-G|}\,. \tag{5}$$

Transversal stability condition $0<\mu(\bar{\varphi})<\pi$ must be valid for all values of $\bar{\varphi}$ from the longitudinal stability region. The expression (4) is obtained using a smooth approximation. More accurate value of transversal oscillations frequency near the parametric resonance can be obtained from Mathieu equation $d^2y/d\xi^2 + y(a_y + q_y\cos 2\xi) = 0$ with the coefficients:

$$a_y = -\frac{4A_s}{(1-G)^2}\sin(\bar{\varphi}+\bar{\varphi}_s) + 2\left(\frac{A_f G}{1-G}\right)^2, \qquad q_y = \frac{2A_f G}{(1-G)^2}\,. \tag{6}$$

Transversal beam current limit I_y is:

$$I_y = \frac{2I_0}{\lambda^2}\,\frac{\Omega_y}{\omega_0}\,\frac{Z_s}{Y_s}\,V_k\left[1-\left(\frac{V_n}{V_k}\right)^2\right], \tag{7}$$

where V_n, V_k are reduced beam emittance and channel acceptance, respectively.

Resonances

The dependence of the syncronous harmonic amplitude upon the transversal coordinate may cause the instability of longitudinal oscillations. The resonances are expected if

$$\frac{1}{\sqrt{I_0(\bar{\eta}_{max}) + I_2(\bar{\eta}_{max})}} < \frac{\Omega_z}{\Omega_y} < 1\,, \tag{8}$$

$$\frac{2}{I_0(\bar{\eta}_{max})} < \frac{\Omega_z}{\Omega_y} < 2\,, \tag{9}$$

where $I_0(\bar{\eta}_{max})$, $I_2(\bar{\eta}_{max})$ are modified Bessel functions. The analogous transversal oscillations instability because of dependence of transversal oscillations frequency on the phase of the particle is expected if

$$0{,}95 < \frac{\Omega_z}{\Omega_y} < 1 \quad ; \quad 1{,}4 < \frac{\Omega_z}{\Omega_y}\,. \tag{10}$$

To avoid these resonances the values of frequencies must be chosen out of the intervals (8), (9), (10).

Nonlinear Field

Nonlinear action of electromagnetic field is defined by a coefficient

$$\varkappa = \frac{T(\bar{\eta}_{max},\bar{\varphi})}{K(\bar{\varphi})\,\bar{\eta}_{max}} - 1\,, \tag{11}$$

where $T(\bar{\eta},\bar{\varphi}) = -A_s\,\mathrm{sh}(\bar{\eta})\sin(\bar{\varphi}+\bar{\varphi}_s) + \frac{G}{2}\left(\frac{A_f}{1-G}\right)^2\mathrm{sh}(2\bar{\eta}G)$ is a nonlinear force, $K(\bar{\varphi}) = -A_s\sin(\bar{\varphi}+\bar{\varphi}_s) + [A_f G/(1-G)]^2$ is a gradient of linear force. The analysis of beam dynamics shows that the linear theory is correct if $\varkappa$ is not larger then 0.1.

Accelerator Design

The accelerating channel design is based on choosing the necessary shape and distribution of electrodes along the structure to provide the optimum RF field spectrum. The computer program developed especially for this purpose is used. Table 1 shows a list of accelerator design parameters.

Table 1. The design parameters of H^- ribbon beam accelerator.

	I stage	II stage
Frequency(MHz)	150	150
Input Energy (MeV)	0.1	0.2
Output Energy (MeV)	0.2	2.0
Resonator Length (m)	1.3	2.6
Number of Gaps	39	107
Vertical Slot Size (cm)	0.8	0.8...1.6
Horizontal Slot Size (cm)	10	10
Phase Stability Region (°)	300...160	160...80
Channel Acceptance (cm.mrad)	0.4	0.4
Max Surface Field (kV/cm)	300	300
Max Beam Current (A)	1	1

The accelerator includes bunching (I) and accelerating (II) sections. The parameters were chosen to provide high transmission efficiency 80% under limited voltage between electrodes 200 kV.

Conclusion

The ribbon beam concept was used as a means of increasing the space charge limited current in RF accelerator for heating thermonuclear plasmas. The focusing by nonsyncronous RF field harmonic was used and the conditions to provide both longitudinal and transversal stability of particles oscillations were found. Calculation stadies show that ribbon beam accelerator is a promising variant of an injector for a high power facility.

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