COULOMB LIMIT FOR ACCELERATING CURRENT IN A LINAC ACCELERATING CHANNEL BASED ON COMBINED RF FOCUSING

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Ion beam propagation stability in an accelerating channel based on combined RF-focusing (CRFF) at high space-charge density is investigated. It is demonstrated that in case of grouped beam acceleration, the Coulomb current limitation for both the proton and the heavy ion beam is higher in case of a CRFF-based channel than for an initial part of any modern accelerator based on RFQ focusing.

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INTRODUCTION

When designing a high-power ion linear accelerator, one of the major tasks is to devise a technique for beam focusing that provides strong focusing and is less complicated than focusing by electromagnetic lenses. It should be pointed out that any modern electromagnetic lens is a very complex technological unit requiring its own cooling system and power supply. As an alternative to the external focusing device, a different approach implying that the accelerating rf field provides stability of charged particle beam propagation is proposed (see Refs. [1 - 7]).

However, despite being promising, rf-based focusing is implemented mainly in an initial accelerator section where energy level is low and almost never in medium-energy one. The only active linear accelerator operating without any external electromagnetic focusing devices is the proton injector URAL-30 which was put into service at the Institute of High-Energy Physics (Russia) in 1981 [8]. A modified version of the alternating phase focusing method (see Refs. [4, 6]) combined with the rf quadrupole focusing technique (see Ref. [1]) when accelerating proton and heavy-ion beams at medium energy is described in Ref. [9].

As for beam propagation stability in both longitudinal and transverse direction in an ion linac accelerating channel which is based on CRFF, the issue is addressed in Ref. [10]. There the values for RFQ field gradient to provide transverse propagation stability for all the particles in an acceleration mode are calculated. It is also shown that such gradients could be achieved in quadrupole gaps considering electrical strength of the electrodes.

Further improvements on the multi-charged ion linear accelerator (MILAC) (see Ref. [11]) such as replacement of grid and magnetic quadrupole focusing for CRFF are presented in Refs. [12, 13]. Design, layout, and adjustment procedures for interdigital IH accelerating CRFF-based structures are discussed in Ref. [14].

This paper objective is to substantiate the possibility of stable acceleration of intense charge-particle beams in a CRFF-based accelerating structure at medium energy.

MATHEMATICAL MODEL. GENERAL EQUATIONS

Notice that at medium energy a beam of charged particles is grouped and could be described as a dense triaxial elliptic bunch that generates Coulomb fields with the following components (see Ref. [15]):

$$E_{sx} = \frac{3I\lambda(1-f)}{4\pi\varepsilon_0 c(r_x+r_y)r_z}\frac{x}{r_x};$$

$$E_{sy} = \frac{3I\lambda(1-f)}{4\pi\varepsilon_0 c(r_x+r_y)r_z}\frac{y}{r_y}; \qquad (1)$$

$$E_{sz} = \frac{3I\lambda f}{4\pi\varepsilon_0 c\, r_x r_y}\frac{z}{r_z}.$$

Here I is the beam current over RF period; λ is the operating wavelength; f stands for the ellipsoid form-factor; ε_0 is the permittivity of free space; c is the speed of light in vacuum; r_x, r_y, and r_z are the ellipsoid axes in a laboratory system of coordinates. The form-factor f depends on the ellipsoid form via parameter $p = \gamma r_z/\sqrt{r_x r_y}$, $\gamma = 1/\sqrt{1-\beta^2}$, $\beta = \upsilon/c$ is the relative velocity of the reference particle; υ is the reference particle velocity. At $p = 1$ the bunch is spherical. At $0.8 < p < 5.0$ the form-factor could be approximated as $f = 1/3p$.

According to Ref. [16], for the above-mentioned beam approximation model the maximum longitudinal and transverse current are expressed respectively as

$$I_{l,\max} = \frac{2\mu_l \beta\gamma a E_0 T \sin(-\varphi_s)|\varphi_s|^2}{Z_0\sqrt{\psi}}, \qquad (2)$$

$$I_{T,\max} = \mu_T \frac{4\pi\varepsilon_0\gamma^3\beta^2 mc^3(r_x+r_y)r_x r_z}{q\lambda(1-f)}\left(\frac{\sigma_0}{P}\right)^2. \qquad (3)$$

Here the phase extent is $2|\varphi_s|$ (φ_s being the reference particle phase); $r_z = |\varphi_s|\beta\lambda/2\pi$; μ_l and μ_T is the ratio of the longitudinal and transverse component of space charge force to the corresponding focusing force (in case of a high-current beam $\mu_l \approx 1$ and $\mu_T \approx 1$); a is the aperture radius where the beam oscillates; E_0T is the amplitude of the equivalent traveling wave; $Z_0 = 1/\varepsilon_0 c = 376.73\,\Omega$; $\psi = r_{x,\max}/r_{y,\min}$; $r_{x,\max} = a$; σ_0 represents the phase shift of radial oscillations over the focusing period at zero current; q stands for the particle charge; $P = N\beta\lambda$ is the focusing period length; N is the integer number.

RESULTS AND DISCUSSION

Let us estimate the maximum current in a channel for two CRFF-based linear accelerators, namely, a proton linac for electronuclear studies and a heavy-ion accelerator for radiative and nuclear physics research, the latter operating at the mass-to-charge ratio $A/q = 20$. Due to the fact that the Coulomb force influence on beam dynamics is maximal at low particle velocities, it is suffice to take into consideration only initial section of these accelerating structures.

First, we calculate using Eqs. (2), (3) the maximum current in case of proton linac taking into consideration the following parameters: the injection energy is 3 MeV; the magnitude of the equivalent traveling wave is 75 kV/cm; the aperture radius a=0.6 cm; the ellipsoid semiaxes ratio $\psi = r_{x,\max} / r_{y,\min} = 2$; the reference particle phase in the axisymmetrical gap $\varphi_s = -17.5°$, the phase extent $2|\varphi_s|$=35°; the phase shift of radial oscillations over the focusing period at zero current σ_0=45°. Thus, for the maximum longitudinal and radial current we obtain

$$I_{l,\max} = 385\ mA\,, \quad I_{T,\max} = 383\ mA\,.$$

As for the case of heavy-ion ($A/q = 20$) linear accelerator, the above-mentioned parameters are almost identical: the injection energy is 2 MeV; the magnitude of the equivalent traveling wave is 40 kV/cm; the aperture radius a=0.7 cm; the ellipsoid semiaxes ratio $\psi = r_{x,\max} / r_{y,\min} = 2$; the reference particle phase in the axisymmetrical gap $\varphi_s = -17.5°$, the phase extent $2|\varphi_s|$=35°; the phase shift of radial oscillations over the focusing period at zero current σ_0=45°. So, the Eqs. (2) and (3) yield the following values

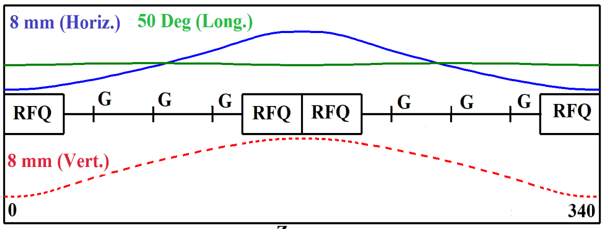
$$I_{l,\max} = 37\ mA\,, \quad I_{T,\max} = 22\ mA\,,$$

for the maximum longitudinal and transverse current respectively.

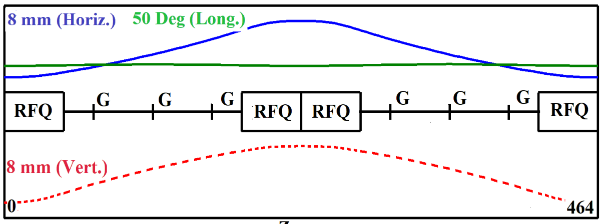
Note that due to complexity of the task, several simplifications have been introduced. Therefore, the calculated maximal current, while rough, is higher than the current generated in the initial section of any modern linac. For instance, the maximum current registered in the RFQ-structure is in the range of 100…150 mA for the proton linac and 5…15 mA for the heavy-ion ($A/q = 20$) accelerator.

Figure presents the beam envelops calculated with the help of Trace-3D code (see Ref. [17]). This code was developed by Los Alamos Accelerator Code Group of Los Alamos National Laboratory. It calculates the envelop evolution of a channel-consistent beam through a focusing section with the space-charge force being accounted for. As the program is interactive and has several user-defined options, we used the following approximations: a particle bunch is represented as a triaxial ellipsoid; a gap action is considered in the approximation of a thin lens.

In the figure, the following notations are used: RFQ – a quadrupole section, G – an axisymmetrical gap center. The beam envelop in the horizontal direction (see Figure, blue solid line) corresponds to the focusing section with the pattern DOOOFFOOOD (with D being the defocusing segment, O standing for the axisymmetrical gap, and F representing the focusing cell), while the pattern corresponding to the beam envelop in the vertical direction (see Figure, red dashed line) is FOOODDOOOF.



a



b

Beam envelop in vertical (dashed red line) and horizontal (solid blue line) direction and phase extent (solid green line in each graph set) over focusing period with CRFF:
a – for protons at 380 mA beam current;
b – for heavy ions $A/q = 20$ *at 22 mA*

CONCLUSIONS

The focusing method suggested allows one to capture and steadily accelerate both light and heavy particle beams inside the initial part of any modern accelerator. Also, contrary to focusing by magnetic lenses, rigidity of CRFF does not depend on particle velocity thus enabling CRFF to be implemented into the low-output-energy initial part of accelerator and in doing so to simplify heavy ion focusing.

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КУЛОНОВСКИЙ ПРЕДЕЛ УСКОРЯЕМОГО ТОКА В КАНАЛАХ ЛИНЕЙНЫХ УСКОРИТЕЛЕЙ ИОНОВ С КОМБИНИРОВАННОЙ ВЫСОКОЧАСТОТНОЙ ФОКУСИРОВКОЙ

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Изучена устойчивость движения ионных пучков в ускоряющих каналах с комбинированной высокочастотной фокусировкой (КВЧФ) при большой плотности пространственного заряда. Показано, что для канала в КВЧФ-структуре, предназначенного для ускорения сгруппированных пучков, кулоновский предел ускоряемого тока как для протонов, так и для тяжелых ионов превышает токи, получаемые в современных линейных ускорителях в начальной части при помощи пространственно-однородной квадрупольной фокусировки.

КУЛОНІВСЬКИЙ ПОРІГ СТРУМУ, ЩО ПРИСКОРЮЄТЬСЯ, У КАНАЛАХ ЛІНІЙНИХ ПРИСКОРЮВАЧІВ З КОМБІНОВАНИМ ВИСОКОЧАСТОТНИМ ФОКУСУВАННЯМ

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Досліджено стійкість руху іонних пучків у каналах, що прискорюють, з комбінованим високочастотним фокусуванням (КВЧФ) при великій густині просторового заряду. Показано, що для каналу в КВЧФ-структурі, який призначено для прискорення згрупованих пучків, кулонівський поріг струму, що прискорюється, для протонів та важких іонів перевищує струми, які отримані в сучасних лінійних прискорювачах у початковій частині за допомогою просторово-однорідного квадрупольного фокусування.