HIGH INTENSITY PROTON BEAM DYNAMICS SIMULATION IN THE INITIAL PART OF ADS LINAC

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One of the most important scientific and technical challenges is the design and development of a new type power reactor, which has a higher nuclear safety. At present several projects related to the so-called hybrid (subcritical) reactors, based on high power proton accelerators, are realized worldwide. Accelerator-driver, as a part of hybrid system (ADS), must meet a number of requirements, among which small losses of the accelerated particles. To fulfill this requirement, it is necessary to ensure small beam emittance at the injector output, exact alignment and work stability of all accelerator parts, a careful study of the beam halo formation and envelope control. On the basis of the developed beam envelope control method main parameters of the linear accelerator-driver initial part which provide high acceleration rate under small particle losses are chosen. Numerical simulation of self-consistent high intensity proton beam dynamics in the initial part of the accelerator-driver is performed.

PACS: 02.30.Em; 41.75.Lx

INTRODUCTION

One of the most urgent problems of accelerator engineering to date is a design and development of high-performance high-current systems for an injection and acceleration of low-velocity proton and ion beams. In particular, 18 countries of the World declared the design and development of systems on the basis of the accelerator drivers (ADS) to date. The most developed projects of these systems, which based on linear accelerators, are MYRRHA (Belgium), ESS (Sweden), IFMIF (Italy) [1 - 3]. In order to ensure the safety and stability of this systems it is used well-tried and proven engineering solutions. The initial part of a linear accelerator-driver is a section with spatially homogeneous quadrupole focusing (RFQ), as a general rule. However, a grave drawback of classical RFQ structures is the relatively low acceleration rate that often leads to an increase of the accelerator driver total length. Structures with RF focusing by means of spatial harmonics (an acceleration rate of which can reach up to 1.5…2 MeV/m under high current transmission) can be used as an alternative to channels with RFQ. In addition, main losses of the particles typically occur in initial parts of the RFQ sections due to Coulomb interaction. Therefore it is necessary to develop an analytical method to control the beam envelope and halo formation. The goals of this work are to present beam dynamics investigation method, which allows one to perform optimization of linac parameters in order to realize beam envelope control, and to define main parameters of structure with RF focusing by means of nonsynchronous spatial harmonic which guarantee high acceleration rate under high current transmission (over 90 %) and halo formation decrease.

1. ANALYTICAL RESULTS

It is difficult to investigate a beam dynamics in a high frequency polyharmonic field. Therefore, one can use a method of an averaging over a rapid oscillations period, following the formalism presented in Ref. [4]. One first expresses RF field in an axisymmetric periodic resonant structure as Fourier's representation by spatial harmonics of a standing wave assuming that the structure period is a slowly varying function of a longitudinal coordinate z

$$E_{\|} = \sum_{n=0}^{\infty} E_n I_0(k_n r)\cos\left(\int k_n dz\right)\cos\omega t;$$
$$E_{\perp} = \sum_{n=0}^{\infty} E_n I_1(k_n r)\sin\left(\int k_n dz\right)\cos\omega t, \quad (1)$$

where E_n is the nth harmonic amplitude of RF field on the axis; $k_n = (\theta + 2\pi n)/D$ is the propagation wave number for the n-th RF field spatial harmonic; D is the resonant structure geometric period; θ is the phase advance per D period; ω is the circular frequency; I_0, I_1 are modified Bessel functions of the first kind.

One has to take into account non-coherent particle oscillations in the beam being accelerated. To this end, one introduces a notion of a reference particle, i.e. a particle moving on the channel axis. This particle is at the point with coordinates (z_r; 0) at given moment of time (subscript "r" means a value for the reference particle). A magnetic force can be neglected for low-energy ions. Assuming that dr/dz << 1 one passes into the reference particle rest frame. There is a differentiation over longitudinal coordinate in the beam motion equation. Thus, the motion equation together with an equation of particle phase variation can be presented in a view of a system of the first order differential equations as follows

$$\begin{cases} \dfrac{d\Theta}{d\xi} = \hat{e}_{\|}(\xi,0,t_r) - \hat{e}_{\|}(\xi,0,t); \\ \dfrac{d\beta_{\perp}}{d\xi} = \dfrac{\hat{e}_{\perp}(\xi,r,t)}{\beta_{\|}}; \\ \dfrac{d\psi}{d\xi} = \dfrac{1}{\beta_{\|}} - \dfrac{1}{\beta_{\|r}}. \end{cases} \quad (2)$$

The following dimensionless variables were introduced here: $\Theta = \gamma_r - \gamma$, γ is the Lorentz's factor; $\xi = 2\pi z/\lambda$, $\hat{e}_{\|,\perp} = eE_{\|,\perp}\lambda/2\pi m_0 c^2$, e is the elementary charge, λ is a wave length of RF field, m_0 is proton rest mass, c is the light velocity in free space; $\beta_{\|,\perp} = \upsilon_{\|,\perp}/c$, $\psi = \omega(t - t_r)$. Note, it can be assumed that $\Theta \approx \beta_s(\beta_{\|r} - \beta_{\|})$, where β_s is the equilibrium particle velocity and s is a number of the synchronous harmonic, provided $|\beta_{\|} - \beta_s| << 1$ is satisfied. Therefore, we can write $d\psi/d\xi \approx (\beta_{\|r} - \beta_{\|})/\beta_s^2$ for the last equation of the system (2). Now the first and the third equations of the system (2) can be united as follows

$$\frac{d^2\psi}{d\xi^2}+3\kappa(\xi)\frac{d\psi}{d\xi}=\frac{1}{\beta_s^3}\frac{d\Theta}{d\xi}, \qquad (3)$$

and the second equation of the system (2) can be rewritten in the form

$$\frac{d^2\delta}{d\xi^2}+\kappa(\xi)\frac{d\delta}{d\xi}=\frac{\hat{e}_\perp}{\beta_s^3}, \qquad (4)$$

where $\delta = 2\pi r/\beta_s\lambda$ is the dimensionless transverse variable and $\kappa = (\ln\beta_s)'_\xi$. On averaging over rapid oscillation period one can present the motion equation in the smooth approximation with the restrictions mentioned above in the following matrix form

$$\ddot{\mathrm{Y}}+\Lambda\dot{\mathrm{Y}}=-\mathrm{L}U_{\mathrm{ef}}, \qquad (5)$$

where the dot above stands for differentiation with respect to the independent ξ variable. Hereafter ψ and δ mean its averaged values and

$$\mathrm{Y}=\begin{pmatrix}\psi\\ \delta\end{pmatrix},\quad \Lambda=\begin{pmatrix}3\kappa & 0\\ 0 & \kappa\end{pmatrix},\quad \mathrm{L}=\begin{pmatrix}\frac{\partial}{\partial\psi}\\ \frac{\partial}{\partial\delta}\end{pmatrix}. \qquad (6)$$

U_{ef} is an effective potential function (EPF) describing a two-dimensional low-energy beam interaction with the polyharmonical field of the system. For Wideroe type structure in the case of two spatial harmonics (one of it is the synchronous harmonic with $n = 0$, and another one is the nonsynchronous with $n = 1$) U_{ef} can be expressed as

$$\begin{aligned}U_{\mathrm{ef}} = &\frac{e_0}{2\beta_s}\left[I_0(\delta)\left(\sin(\psi+\phi_r)-\psi\cos\phi_r-\sin\phi_r\right)\right]\\ &+\frac{e_0^2}{64}\left[I_0^2(\delta)+I_1^2(\delta)-1\right]+\frac{5e_1^2}{256}\left[I_0^2(3\delta)+I_1^2(3\delta)-1\right]\\ &-\frac{e_0^2}{32}\left[I_0(\delta)\cos\psi-1\right]+\frac{5e_0^2}{128}\left[I_0(3\delta)\cos\psi-1\right]\\ &-\frac{e_0e_1}{32}\left\{\left[I_0(\delta)+I_0(3\delta)\right]\left[\cos(\psi+2\phi_r)-2\cos2\phi_r\right]\right\}\\ &+\frac{e_0e_1}{32}\left\{\left[I_0(\delta)I_0(3\delta)+I_1(\delta)I_1(3\delta)\right]\left[\cos2(\psi+\phi_r)-\cos2\phi_r\right]\right\}.\end{aligned} \qquad (7)$$

Here $e_n = eE_n\lambda/2\pi\beta_s^2 m_0c^2$; ϕ_r is the reference particle phase.

To define eigenfrequencies of small system vibrations, EPF is expanded in Maclaurin's series

$$U_{\mathrm{ef}}=\frac{\Omega_{0\psi}^2\psi^2}{2}+\frac{\Omega_{0\delta}^2\delta^2}{2}+o\left(\mathrm{Y}^{\mathrm{T}}\mathrm{Y}\right) \qquad (8)$$

and the coefficients in which are given by

$$\begin{aligned}\Omega_{0\psi}^2 &= -\frac{e_0}{2\beta_s}\sin\phi_r-\frac{e_0e_1}{16}\cos2\phi_r+\frac{e_0^2}{32}+\frac{5e_1^2}{128},\\ \Omega_{0\delta}^2 &= \frac{e_0}{4\beta_s}\sin\phi_r+\frac{3e_0e_1}{64}\cos2\phi_r+\frac{e_0^2}{128}+\frac{45e_1^2}{512}.\end{aligned} \qquad (9)$$

A character of the vibrations will depend on ratio between the dissipative coefficient κ and eigenfrequencies. It is necessary that $\Omega_{0\psi}^2 > 0$, $\Omega_{0\delta}^2 > 0$ for the beam envelope has no increase.

2. NUMERICAL RESULTS

Linac parameters with RF focusing by means of one nonsynchronous spatial harmonic were optimized by using numerical self-consistent low-energy proton beam dynamics simulation after beam dynamics optimization in one particle approximation on the basis of obtained analytical results was carried out. Self-consistent beam dynamics simulations were performed by using a modified version of the specialized computer code BEAMDULAC-ARF3 based on CIC technique to calculate beam self-space-charge field. To ensure high current transmission (over 90%) special optimization of the field change law was done. It was based on the supposition that channel acceptance is a nondecreasing function of the longitudinal beam coordinate. Therefore, taking into account the equation of motion for the equilibrium particle, the law of the synchronous harmonic amplitude variation at a field increasing length can be written as

$$\begin{aligned}\frac{d\hat{e}_0}{d\xi}=&\frac{\hat{e}_0}{\ell}\frac{d\ell}{d\xi}-\frac{\hat{e}_0}{\varsigma}\frac{d\varsigma}{d\xi}-\frac{\hat{e}_0^3\cos\phi_s}{\hat{e}_0(0)\beta_s(0)\varsigma(0)}\frac{\varsigma}{\ell}\\ &-\frac{\chi\sin2\phi_s}{8\hat{e}_0^{1.5}(0)\varsigma^{1.5}(0)\beta_s^8(0)}\left(\frac{\hat{e}_0\varsigma}{\ell}\right)^{1.5},\end{aligned} \qquad (10)$$

where ℓ is a certain function of ξ, ς is a longitudinal acceptance phase width, φ_s is the equilibrium particle phase in the synchronous harmonic field, χ is the amplitude ratio (e_1/e_0).

Main linac parameters are listed in Table 1. A variation of the linac parameters are shown in Fig. 1.

Table 1

Main linac parameters

Parameter	Value
Operational frequency, MHz	176.105
Total linac length, m	2
Bunching length, m	1.7
Input equilibrium particle phase	−90°
Output equilibrium particle phase	−22.5°
Input synchronous harmonic amplitude, kV/cm	0.5
Amplitude ratio	7.4
Linac half-aperture, mm	5

For example, summarized in Table 2 beam parameters were used for simulation. It is clearly that input transversal emittance for ADS linac (about 0.2π mm·mrad) much smaller that presented in Table 2, but latter one was used to illustrate an effectiveness of the linac with RF focusing by means of nonsynchronous spatial harmonics.

Table 2

Input beam parameters

Parameter	Value
Particle	p
Input energy, keV	65
Input energy spread, %	1
Input radius, mm	2,5
Input transversal emittance, π·mm·mrad	18
Input beam current, mA	10

The output beam particles phase portraits are shown in Fig. 2,a (color indicates particle density) and Fig. 2,b (color indicates particles in corresponding scattering ellipses). From this Figures one can see that beam has rather good quality.

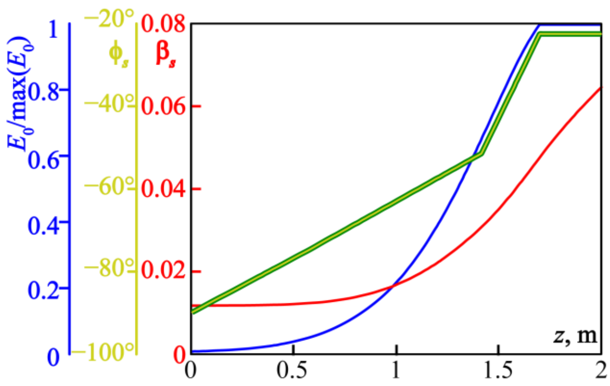

Fig. 1. Main linac parameters

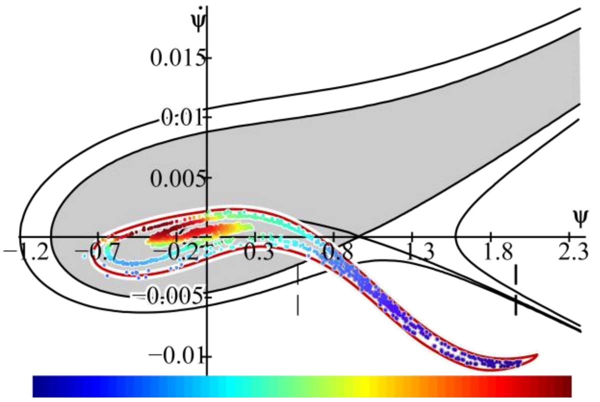

Fig. 2,a. Output longitudinal beam particles distribution

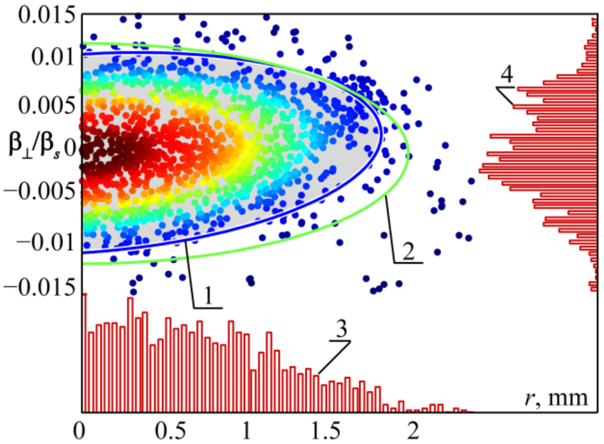

Fig. 2,b. Output transversal beam particles distribution 1 – RMS emittance; 2 – Floquet ellipse; 3 – histogram of particles distribution by radii; 4 – histogram of particles distribution by transverse velocity components

Beam maximal radius variation along linac is shown in Fig. 3,a. As one can see there is no beam radius increase as well as transversal emittance one at the linac output. Main particle losses arise from not quite adiabatic bunching process and it is observed in longitudinal phase space mainly (Fig. 3,b).

Halo is an intrinsic property of the beam as it was stated in [5]. To estimate the halo one can use results presented in [5] by supposing that the motion is uncoupled between phase planes (that is right for axial region). Thus halo parameter has the next form

$$H = \frac{\sqrt{3\mu_{0,4}\mu_{4,0} + 9\mu_{2,2}^2 - 12\mu_{1,3}\mu_{3,1}}}{2\mu_{0,2}\mu_{2,0} - 2\mu_{1,1}^2} - 2, \qquad (11)$$

where $\mu_{n,k}$ is the central moment of the order n, s in $(r, dr/dz)$ system.

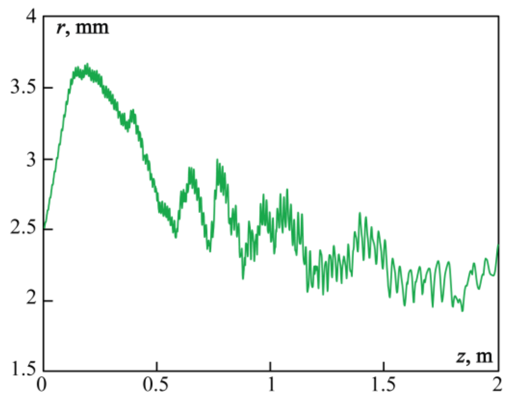

Fig. 3,a. Beam envelope

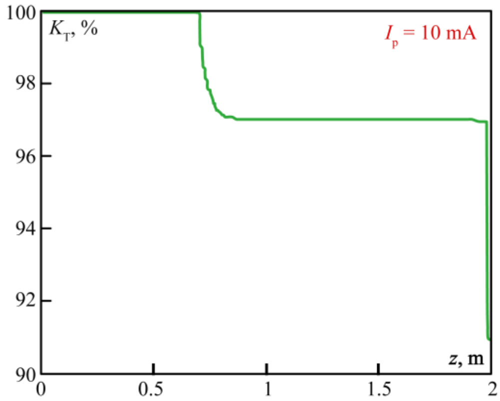

Fig. 3,b. Transmission vs longitudinal coordinate

The behavior of the halo parameter is illustrated in Fig. 4. Significant halo formation in the 2D phase-space corresponds to $H > 1$ as it is showed by carried out simulations.

Output beam parameters are listed in Table 3.

Table 3

Output beam parameters

Parameter	Value
Output energy, MeV	2
Ouput radius, mm	2,5
Output transversal emittance, π·mm·mrad	18
Current transmission, %	91

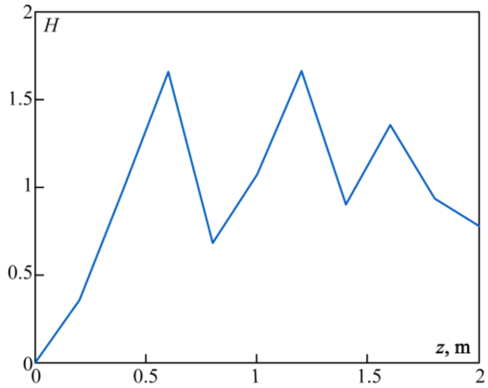

Fig. 4. Halo parameter vs longitudinal coordinate

Variation of the linac current transmission coefficient under different input beam currents is shown in Fig. 5.

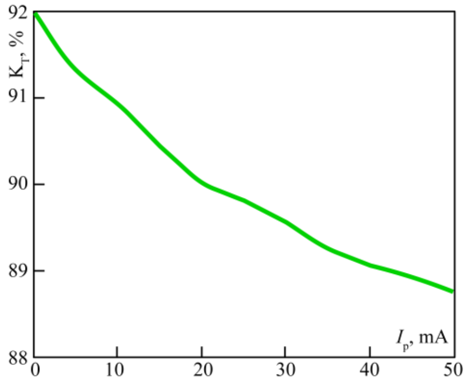

Fig. 5. Current transmission coefficient vs initial proton beam current

SUMMARY

The necessary requirements to ensure beam envelope preservation were formulated. The main parameters of linear accelerator-driver front-end part were chosen. There are no beam envelope overgrowth and significant halo formation under chosen parameters at the linac output. Numerical simulation of self-consistent beam dynamics confirmed the analytical results.

ACKNOWLEDGEMENTS

This work is supported in part by the Ministry of Science and Education of Russian Federation under contracts No. 14.A18.21.1568 and 14.516.11.0084.

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Article received 06.09.2013

МОДЕЛИРОВАНИЕ ДИНАМИКИ СИЛЬНОТОЧНОГО ПРОТОННОГО ПУЧКА В НАЧАЛЬНОЙ ЧАСТИ УСКОРИТЕЛЯ-ДРАЙВЕРА ДЛЯ ГИБРИДНЫХ СИСТЕМ

В.С. Дюбков

Одной из актуальных научно-технических задач является разработка и создание нового типа энергетического реактора, обладающего повышенной ядерной безопасностью. В настоящее время в мире реализуется несколько проектов, связанных с так называемыми гибридными (подкритическими) реакторами, строящимися на базе протонных ускорителей большой мощности. К ускорителю-драйверу протонных пучков, входящему в состав гибридной системы, предъявляется ряд достаточно жестких требований, среди которых обеспечение сверхмалых потерь ускоряемых частиц. Для выполнения этого требования необходимо обеспечить малое значение эмиттанса пучка на выходе инжектора, точное согласование и стабильность работы всех частей ускорителя, тщательное исследование образования ореола пучка и контроль его огибающей. В данной работе на основании разработанного метода контроля за огибающей пучка выбираются основные параметры начальной части линейного ускорителя-драйвера, обеспечивающие высокий темп ускорения при малых потерях частиц. Проводится численное моделирование самосогласованного сильноточного протонного пучка в начальной части ускорителя-драйвера.

МОДЕЛЮВАННЯ ДИНАМІКИ ПОТУЖНОСТРУМОВОГО ПРОТОННОГО ПУЧКА В ПОЧАТКОВІЙ ЧАСТИНИ ПРИСКОРЮВАЧА-ДРАЙВЕРА ДЛЯ ГІБРИДНИХ СИСТЕМ

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Одним з актуальних науково-технічних завдань є розробка і створення нового типу енергетичного реактора, що має підвищену ядерну безпеку. В даний час у світі реалізується кілька проектів, пов'язаних з так званими гібридними (підкритичними) реакторами, що будуються на базі протонних прискорювачів великої потужності. До прискорювача-драйвера протонних пучків, що входить до складу гібридної системи, пред'являється ряд досить жорстких вимог, серед яких забезпечення щонайменших втрат прискорених частинок. Для виконання цієї вимоги необхідно забезпечити мале значення еміттансу пучка на виході інжектора, точне узгодження і стабільність роботи всіх частин прискорювача, ретельне дослідження утворення ореола пучка і контроль його огинаючої. У цій роботі на підставі розробленого методу контролю за огинаючою пучка вибираються основні параметри початкової частини лінійного прискорювача-драйвера, що забезпечують високий темп прискорення за малих втрат частинок. Проводиться чисельне моделювання самоузгодженого потужнострумового протонного пучка в початковій частині прискорювача-драйвера.