RESULTS OF THE USE OF AXISYMMETRIC RF FOCUSING IN PROTON LINACS AT ENERGIES UP TO 7 MeV

V. S. Dyubkov, Ya. V. Shashkov, National Research Nuclear University “MEPhI”, Moscow, Russia

Abstract

During a few decades axisymmetric RF structures with a focusing by means of nonsynchronous spatial harmonics of electromagnetic field are offered instead of proven RFQ. An effectiveness of these structures in the energy range up to 2 MeV was shown in a number of papers. An effectiveness of these structures in the energy range up to 7 MeV is considered in this paper. Results of an analytical investigation and a numerical simulation of self-consistent proton dynamics are presented and discussed.

INTRODUCTION

It is well known that proton and ion accelerators are used for medical radionuclide production, as well as for radiation therapy. Radionuclide production mainly is performed by means of cyclotrons and reactors. There are several commercial companies with a number of basic cyclotrons (Advanced Cyclotron Systems Inc., Advanced Biomarkers Technology, Best Cyclotrons Systems Inc., GE Healthcare, IBA, Siemens, JSC “Efremov Institute of Electrophysical Apparatus” and other). The cyclotrons are well recommended and reliable machines. Nevertheless there are some aspects of cyclotrons related to biological shield, to high weight, as well as to its rather high power supply [1]. However, it is worth noting that there are a few projects of superconducting cyclotron development to make light weight compact machine [2]. Systems based on linacs are free from these problems. The most widely used radioisotope for non-invasive PET is the short-lived positron emitter ^{18}F. Portable complexes PULSAR$^{\text{TM}}$ 7 (AccSys Technology Inc.) for ^{18}F production are commercially realized nowadays [3]. The PULSAR$^{\text{TM}}$ 7 linac consists of 3.5 MeV section with RFQ and 3.5 MeV DTL. This linac provides protons with energy are equal to 7 MeV. There is a project of $^{3}He^{2+}$ RFQ accelerator for the PET isotope production [4]. This 10.5 MeV linac was planned to be based on RFQ sections only. Possibilities of PET isotope production by means of linear deuteron accelerator and tandem one are discussed in [5, 6]. There are several proposals to use initial parts of the existing middle energy linacs (up to 200 MeV) for PET radionuclide production in scientific centers [7, 8]. A possibility of using the RF focusing by means of the nonsynchronous spatial electromagnetic (EM) field harmonic at proton linac with energy up to 7 MeV is considered in this paper and suggested as a part of PET isotope production complex. A structure with RF focusing by means of the nonsynchronous spatial EM field harmonic is regarded as alternative to structure with RFQ for protons energies up to 3 MeV traditionally. This structure allows one to increase beam current in compare with RFQ structure. An effectiveness of applying the RF focusing by means of the nonsynchronous harmonic for low energy protons was presented in the earlier papers [9, 10]. The main goal of current paper is to investigate applying the RF focusing by means of the nonsynchronous harmonic for protons with energies in the range from 2 MeV to 7 MeV.

ANALYTICAL DATA

The analytical investigation of the beam dynamics in a polyharmonical field is a difficult mathematical problem. Rapid longitudinal and transverse oscillations as well as a strong dependence of field components on transverse coordinates do not allow one to use the linear approximation in the paraxial region for a field series. Nevertheless, the analytical beam dynamics investigation in the oscillating fields can be carried out by means of a smooth approximation. RF field is expressed as the Fourier expansion by the standing wave spatial harmonics in an axisymmetric periodic resonant structure as it was done in [10], assuming that the structure period is a slowly varying function of the longitudinal coordinate.

$$E_{\parallel} = \sum_{n=0}^{\infty} E_n I_0(k_n r)\cos\left(\int k_n dz\right)\cos\omega t;$$
$$E_{\perp} = \sum_{n=0}^{\infty} E_n I_1(k_n r)\sin\left(\int k_n dz\right)\cos\omega t;$$
$$k_n = (\theta + 2\pi n)/D,$$

where E_n is the nth harmonic amplitude of RF field on the axis; k_n is the propagation wave number for the nth 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.

It is considered here that there are two spatial harmonics at the linac only. One of it is the synchronous harmonic with $s = 0$, and another one the nonsynchronous (focusing) with $n = 1$. In order to estimate basic linac parameters one can use results presented in [10] for the mentioned conditions and $\theta = \pi$. Thus, one can write the following expressions for squares of eigenfrequencies of small linear vibrations:

$$\omega_{\parallel}^2 = -\frac{1}{2}e_0\sin\varphi_s - \frac{1}{16}e_0 e_1\cos 2\varphi_s + \frac{1}{32}e_0^2 + \frac{5}{128}e_1^2;$$
$$\omega_{\perp}^2 = \frac{1}{4}e_0\sin\varphi_s + \frac{3}{64}e_0 e_1\cos 2\varphi_s + \frac{1}{128}e_0^2 + \frac{45}{512}e_1^2,$$

where

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$$e_i = \frac{eE_i\lambda}{2\pi m\beta_s c^2},$$

e and m are a charge and a mass of particle, λ is a free-space RF wavelength, c is the speed of light, β_s is a normalized velocity of the synchronous particle and φ_s is a synchronous particle phase. It is necessary that the parameters of the channel will be chosen in terms of the conditions $\omega_\parallel^2 > 0$ and $\omega_\perp^2 > 0$ (for the simultaneous transverse and longitudinal focusing).

NUMERICAL SIMULATION RESULTS

Self-consistent beam dynamics simulations were performed by means of a specialized computer code BEAMDULAC–ARF3 based on CIC technique.

On the basis of the eigenfrequencies analysis the following fixed basic parameters of linac sections were chosen and presented in a Table 1.

Table 1: Basic linac parameters

Perameter	Section I	Section II
Frequency	162 MHz	162 MHz
Length	2 m	2 m
φ_s	−60°	−52°
e_0/e_1	0.11	0.14
Synchronous harmonic amplitude	36.4 kV/cm	48.7 kV/cm
Half-aperture	6 mm	6 mm

The following input beam parameters were used for a simulation in the first linac section: injection energy was equal to 2 MeV, energy spread – 30%, phase width – 190°, radius – 2.5 mm, current – 50 mA, transversal rms emittance – 1.5π mm·mrad. Particle distributions in the longitudinal and transversal phase spaces were uniform and “water-bag” respectively.

Beam emittances at the first section exit plane are presented in Fig. 1 and Fig. 2. One can see that the beam radius increased slightly under chosen parameters of the first linac section. Output beam energy was equal to 4 MeV and output transversal rms emittance – 7π mm·mrad under 97% current transmission.

Further, computer simulation of self-consistent beam dynamics was carried out for the second section supposing that the proton beam was injected into the second section entrance directly.

Beam emittances at the second section output are presented in Fig. 3 and Fig. 4. Output beam energy was equal to 7 MeV, output transversal rms emittance – 9π mm·mrad, current transmission – 79%. Thus, the net current transmission coefficient is equal to 77% approximately.

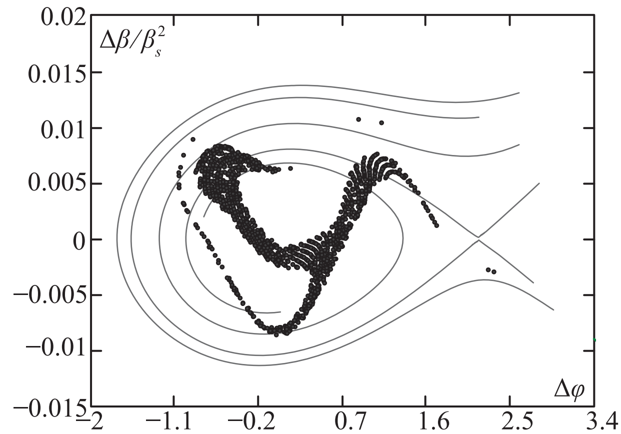

Figure 1: Longitudinal particles distribution at the exit plane of the section I.

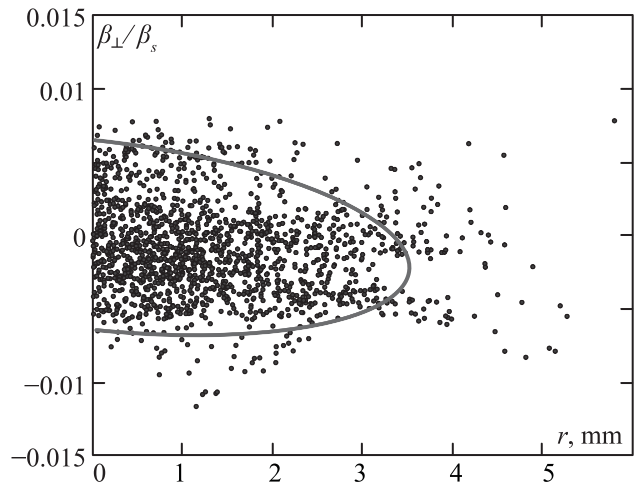

Figure 2: Transversal particles distribution at the exit plane of the section I.

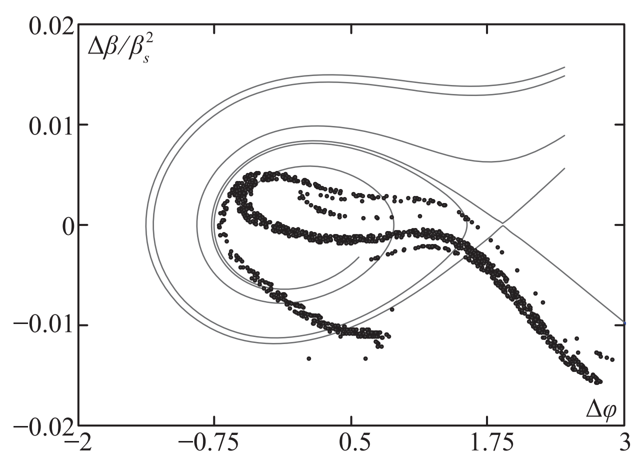

Figure 3: Longitudinal particles distribution at the exit plane of the section II.

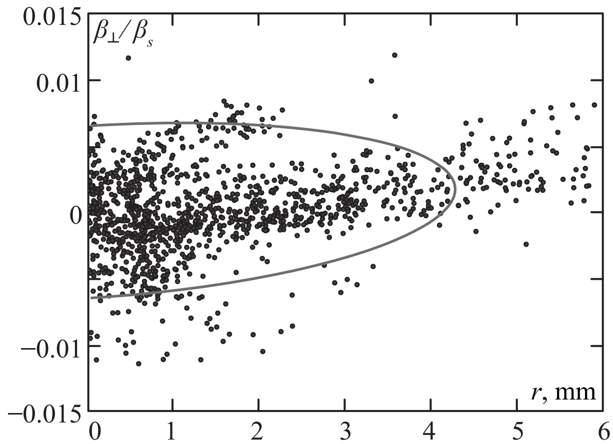

Figure 4: Transversal particles distribution at the exit plane of the section II.

Numerical simulations showed that a rigidity of RF focusing by means of the first spatial harmonic decreased in the energy range from 5 to 7 MeV under chosen parameters. One can notice that beam has rather good quality in the energy range from 2 to 5 MeV and beam quality deteriorates at higher energies.

CONCLUSION

Using the π-mode structures with the focusing by means of the first spatial harmonic of accelerating field in proton energy range from 2 MeV to 7 MeV is considered. It is shown that the focusing technique considered can be used at 7 MeV proton linac with some reservations.

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