Results of using the axisymmetric RF focusing by means of field spatial harmonics at 7 MeV proton linac

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Abstract. For several decades, axially symmetric channels with RF focusing by means of nonsynchronous spatial harmonics of the accelerating field are offered as an attractive alternative to proven and reliable RFQ linacs. In a number of works an effectiveness of channels with axially symmetric RF focusing by means of the nonsynchronous harmonics of the field was demonstrated in the proton energy range up to 2 MeV. An effectiveness of discussed channels for protons at energies up to 7 MeV is considered in this paper. Numerical simulation results of proton self-consistent dynamics in a channel with axisymmetric RF focusing are presented and discussed in this article.

1. Introduction

The emergence of particle accelerators stimulated a development of various fields of science. In turn there has been a rapid growth of the industry and its applications. Today modern high-tech medicine cannot exist without accelerators. Proton and ion accelerators are used for medical radionuclide production, as well as for radiation therapy. Generally radionuclide production is performed by means of cyclotrons, to be used for medical diagnostics (18F, 13N, 15O, 64Cu, 67Ga, 68Ga, 111In, 123I, 124I, 81Kr, 85Mo, 82Rb, 203Tl) or therapies (67Cu, 57Co, 82Sr, 68Ge) in nuclear medicine [1]. 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 [2]. Systems based on linacs are free from these weak points. It makes sense to enlarge the use of linacs for positron emission tomography (PET) isotopes production. The widely used radioisotope for non-invasive PET is the short-lived positron emitter 18F. It can be produced due to reactions 18O(p,n)18F, 20Ne(d,α)18F, 17O(d,n)18F. Portable complexes PULSAR™ 7 (AccSys Technology Inc.) for 18F production, based on linac, exist and it is commercially realized nowadays [3]. The PULSAR™ 7 linac consists of 3.5 MeV RFQ part and 3.5 MeV DTL, which provides protons with energy equal to 7 MeV. There is a project of 1He2+ RFQ accelerator for the production of PET isotopes [4, 5]. This 10.5 MeV linac was planned to be based on RFQ sections only. Possible PET isotope production using linear deuteron accelerators is discussed in [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 [7–9]. A possibility of using the RF

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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 [10]. 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 [11, 12]. 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.

2. Basic relations

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 the 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 [11], assuming that the structure period is a slowly varying function of the longitudinal coordinate.

where \( E_n \) is the \( n \)th harmonic amplitude of RF field on the axis; \( k_n \) is the propagation wave number for the \( n \)th RF field spatial harmonic; \( D \) is the resonant structure geometric period; \( \theta \) is the phase advance per \( D \) period; \( \omega \) 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. One of it is the synchronous harmonic with \( s = 0 \), and another one is the nonsynchronous (focusing) with \( n = 1 \). In order to estimate basic linac parameters one can use results presented in [11] for the mentioned conditions and \( \theta = \pi \). Thus, one can write the following expressions for squares of eigenfrequencies of small linear vibrations:

\[
\omega_{||}^2 = -\frac{1}{2} e_0 \sin \varphi_s - \frac{1}{8} e_0 e_1 \cos 2\varphi_s, \tag{1}
\]

\[
\omega_{\perp}^2 = \frac{1}{4} e_0 \sin \varphi_s + \frac{13}{64} e_0 e_1 \cos 2\varphi_s + \frac{3}{128} e_0^2 + \frac{135}{512} e_1^2, \tag{2}
\]

where

\[
e_1 = \frac{eE_0 \lambda}{2 m n \beta_s c^2}
\]

\( e \) and \( m \) are a charge and a mass of particle, \( \lambda \) is a free-space RF wavelength, \( c \) is the speed of light, \( \beta_s \) is the normalized velocity of the synchronous (equilibrium) particle and \( \varphi_s \) is the synchronous particle phase. It is necessary that the parameters of the channel will be chosen in terms of the conditions \( \omega_{||}^2 > 0 \) and \( \omega_{\perp}^2 > 0 \) (for the simultaneous transverse and longitudinal focusing). In terms of the equation (2) one can obtain a set of curves defining threshold value of \( e_0 / e_1 \) versus \( \varphi_s \) under different \( e_1 \) value (for instance see figure 1).
On the basis of the eigenfrequencies analysis the following fixed basic parameters of linac sections are chosen and presented in the table 1.

![Figure 1. Harmonics amplitudes ratio vs equilibrium particle phase.](image)

**Figure 1.** Harmonics amplitudes ratio vs equilibrium particle phase.

**Table 1.** Basic linac parameters.

| Parameter                           | Section 1 | Section 2 |
|-------------------------------------|-----------|-----------|
| Operational frequency, MHz         | 162       | 162       |
| Section length, m                   | 2         | 2         |
| Linac half-aperture, mm             | 5         | 5         |
| Equilibrium particle phase          | −60°      | −45°      |
| Eynchronous harmonic amplitude, kV/cm| 36        | 40        |
| Harmonics amplitudes ratio, %       | 11        | 12        |

3. **Numerical simulation results**

Self-consistent beam dynamics simulations were conducted by means of a modified version of the specialized computer code BEAMDULAC-ARF3 based on CIC technique to calculate beam self-space-charge field [10].

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 – 100 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 output are presented in figure 2 (line 1 is rms emittance and 2 is Floquet ellipse at the part b of figure). 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 – 8π mm·mrad under 99% current transmission.
Further, computer simulation of self-consistent beam dynamics was carried out for the second section. In order to evaluate the effectiveness of RF focusing by means of the nonsynchronous harmonic in the proton energy range from 4 MeV to 7 MeV the following beam parameters were used: injection energy was equal to 4 MeV, energy spread – 30%, phase width – 130°, radius – 2.5 mm, current – 100 mA, transversal rms emittance – π mm·mrad. Particle distributions in the longitudinal and transversal phase spaces were the same as for the first section. Note, that synchronous phase value was changed along this section unlike the first section where it was the constant.

Beam emittances at the second section output are presented in figure 3. Output beam energy was equal to 7 MeV, output transversal rms emittance – 5π mm·mrad, current transmission – 96%.

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. The particle loss is observed in the transversal direction. For the rigidity of RF focusing to be increased maximal amplitude value of electric field must be ramped up and/or harmonics amplitudes ratio must be decreased for the fixed value of equilibrium particle phase. Note, that maximal amplitude value of electric field is limited by field value at which discharges appear (Kilpatrick limit). In turn, small value of harmonics amplitudes ratio leads to energy gain decrease.
4. Conclusion
Using the \( \pi \)-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. Self-consistent proton beam dynamics simulations were carried out. It is shown that the focusing technique considered can be used at 7 MeV proton linacs, which can be used for PET isotope production and neutron generation.

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