THE CHOICE OF ACCELERATION STRUCTURE FOR PET–SYSTEM

O.I.Drivotin, A.E.Loukianova, D.A.Ovsyannikov,
St.-Petersburg State University, St.-Petersburg, Russia
Yu.N.Gavrish, Yu.A.Svistunov, M.F.Vorogushin
D.V.Efremov Scientific Research Institute of Electrophysical Apparatus

Abstract

Possible schemes of RF linacs for PET isotopes production are considered, RFQ as first stage and drift-tube H-resonator as second stage are proposed. Original software environment has been developed that allows to compute electrode's geometry of RFQ and gap geometry of alternate phase focusing (APF) drift-tube structure with aid of mathematical methods of beam dynamics optimization. RF system is based on endotron type devices. Results of particle dynamics modelling are given. [1]

1 INTRODUCTION

There are few of RF linac project or operating RF linacs for medical isotopes production in the world. They are 425 MHz 11 Mev proton linac of Accsys. Technology with 2 MeV RFQ and drift-tube linac as final part, 8 MeV He^{++} ion linac of SAIC with two of accelerating parts (the first stage is 212,5 MHz, 2.5 MeV He^{+} RFQ, the second stage is 425 MHz, 8 MeV He^{++} RFQ that accelerates He^{++} ions after recharging He^{+} on intermediate target), 3–4 MeV deutron's or He^{+} 200 MHz RFQ of DEFCO. The last one produces F^{18} and O^{15} isotopes only. D.V. Efremov Institute's proposal is 5 or 8 MeV deutron RF linac that has two of accelerating parts: RFQ as first stage and drift tube H-resonator with alternate phase focusing of the beam as second stage. NPK LUTZ department of the Efremov Institute is developing technology of fabricating of ion 433 MHz linacs. Now sample of such linac is tested under laboratory conditions. It is 2 MeV RFQ for $\mathrm{H}^{\pm}$ ion acceleration [1]. For accelerating these ions up to $5 \ldots 15$ MeV, 2 Mev RFQ linac may be used as initial part of accelerator (IPA). It is proposed to accelerate particles from 2 up to $5 \ldots 15$ MeV in the drift-tube cavity. Protons or deutrons of such energies can be used for medical isotope production. Usually Alvarez structure is used as second stage of accelerator. Disadvanteges of Alvarez resonators as part of industrial installation are complexity of tuning, nessesity of special arrangements for alignment of drift tubes, hardness of intensive cooling under big average power and, as consequence, high cost of fabrication and operation. Instead of Alvarez here is proposed structure with crossed transversal holders (CTH), that works on $\pi-$ mode. Electromagnetic field distribution for working type oscillation is according to H(TE) mode. The structure has separate cells, each of them includes broad outer cilindrical ring. Inside of rings drift tubes are fastened on massive holders. Cells can revolve each relative others independently around longitudinal axis. Adjacent cells are oriented such that their holders are located at right angle each to other (or nearly to this position). CTH structure has high mechanical stifness,may have intensive forced cooling need not special arrangement. It's technology of fabrication is close to traditional technology waveguide fabrication.

[1]This work is supported in part by the Russian Foundation for Fundamental Researches 96-01-00926-a

2 MAIN CHARACTERISTICS OF ACCELERATOR

Main blocks of accelerating system and RF system were fabricated and tested as laboratory installation. Here is given brief description of installation's parts and their main parameters. Layout of RF linac for PET is given on Fig.1.

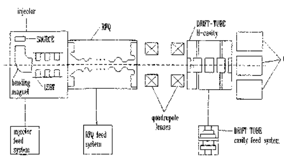

Fig.1.

2.1 Injection system

Injector was tested with plasma surface source producing H^{+} or H^{-} ions. It is proposed next time to work with D^{+} ions. Injection system includes: discharge chamber with plasma surface source of Penning geometry, bending magnet which separates the ion beam D^{+} or D^{-} from impurity, electrostatic LEBT system that focuses and accelerates the ion beam from $15 \ldots 20$ keV (extracting voltage) up to 60 keV. Last system includes set of electrodes. Number, placement and potentials of electrodes are determined by required output beam parameters. Emission slit has sizes $0.4 \times 7\mathrm{mm}^2$. Magnetic field of discharge chamber is formed by poles of bending permanent magnets of KC-37 type. Possible current of D^{+} ions is $15 \ldots 20$ ma, length of current pulse is 100 $\mu\mathrm{sec}$. According to theoretical data and results of measurements $\mathrm{H}^{\pm}$ beam emittances D^{+} normalized emittance may be $E_{nx} \simeq 10^{-7}\mathrm{rad}\cdot\mathrm{m},\ E_{ny} \simeq 10^{-6}\mathrm{rad}\cdot\mathrm{m}$.

2.2 Accelerating structures

The first stage of accelerator is RFQ. The operating parameters are given in table 1.

Table 1. RFQ Parameters.

Accelerated particles	D^+ or D^-
Operating frequency	433 MHz
Input D^+ ion energy	60 keV
Output D^+ ion energy	2 Mev
Pulse current D^+	up to 20 mA
Final synchronous phase	30 degrees
Average bore radius	3.5 mm
Intervane voltage	98 kV
Vane length	3 m
Beam transmission	80 %
Output emittance (norm., theor.)	$10^{-6}\mathrm{rad}\cdot\mathrm{m}$
Quality factor	8600

Cavity is manufactured from aluminium alloy. An accuracy of producing of vane modulation is $10\ldots20$ microns. Inner surfaces of cavity are coppered by electroplating. Second stage of accelerator is drift-tube H-resonator, using AP-focusing for radial and longitudinal beam stabilization. The operating parameters of drift tubes linac are given in the table 2.

Table 2. Drift-Tube Resonator Parameters.

Accelerated particles	D^+ or D^-
Operating frequency	433 MHz
Input ion energy	2 MeV
Output ion energy	5 (8) Mev
Gap's number	44(73)
Cavity length	1.1 (2.02)m
Increasing of aperture radius	from 3 to 6 mm
Maximal field strength on the axis	170 kV/cm
Beam transmission	100 %
Energy spread at output	$\pm 0.6\%$
Quality factor	11300
Output emittance (norm., theor.)	$3\cdot10^{-6}\mathrm{rad}\cdot\mathrm{m}$

2.3 RF system

RF power supply system includes following fundamental units: master oscillator, two of amplification cascades of power, pulse source of anode supply, source of filament supply, source of synchronizing pulses, RF coupling components for power feed with the structure, automatic control systems of amplitude and phase of RF field. If final energy of particles is 5 MeV, only one RF module is need for RFQ supply and only one for drift tube cavity. Endotron type device KIWI is used as power amplifier of output cascade. Principal parameters of RF amplifier are given in table 3.

Table 3. Principle Parameters of RF Amplifier.

RF generator type	endotron KIWI
Operating frequency	433 MHz
Pulse power	up to 500 kW
Pulse length	up to 150 μsec
Average power (max)	8 kW
Pulse repetition	up to 100 Hz
Efficiency	50 %

3 MATHEMATICAL CONTROL MODEL

Assume that charged particles beam can be considered as a dynamical system describing by the equations

$$\begin{cases} dZ/dt = f(t,Z,U) \\ dX/dt = h(t,Z,X,U) \end{cases} \tag{1}$$

where Z, X are vectors characterizing longitudinal and transverse motion correspondingly, $U = U(t)$ is control vector, $Z \in R^n, X \in R^m, U(t) \in K \subset R^l, t \in [0,T]$, $T < \infty$. The initial values of Z are supposed to fill some compact set $M_0 : Z(0) \in M_0 \subset R^m$ and $X(0) = X_0$.

The problem is to minimize the functional which depends on intermediate and terminal densities of particle distribution

$$I(U) = \int_0^T \int_{M_{t,U}} g(t, Z_t, X(t,Z_t), \varrho(t,Z_t))\, dZ_t\, dt +$$

$$\int_{M_{T,U}} G(Z_T, X(T,Z_T)\varrho(T,Z_T))\, dZ_T \tag{2}$$

where g and G are some integrable on t, Z and differentiable on Z and X functions characterizing the quality of the beam. $\varrho(t,Z)$ is particles distribution, $\varrho(0,Z) = \varrho_0(Z),\ Z \in M_0$.

For such problem we can apply general approach (see [3]) taking into account that integral on some components of the phase vector, namely X, reduces to the only value of the integrand. The method of optimization is based on the expression for functional variation.

4 MODELS OF BEAM DYNAMICS

Suppose the particles of the beam entering to the RFQ channel fill some ellipses in the planes x, x' and y, y' where x, y are transverse coordinates and the motions in these planes are independent (i.e. angular momentum is neglected). As the transverse motion equations are supposed linear, the particles fill some ellipses at all following instants. Therefore, we can introduce 6 variables which are elements of inverse matrices of these ellipses: $s^x_{11},\ s^x_{12},\ s^x_{22},\ s^y_{11},\ s^y_{12},\ s^y_{22}$ for every $Z \in M_{t,U}$. They satisfy the following equations [2,3]

$$\begin{cases} ds_{11}^{x,y}/dt = 2\, s_{12}^{x,y} \\ ds_{12}^{x,y}/dt = Q_{x,y} s_{11}^{x,y} + s_{22}^{x,y} \\ ds_{22}^{x,y}/dt = 2\, Q_{x,y} s_{12}^{x,y} \end{cases} \quad (3)$$

where $Q_{x,y} = \dfrac{e\,U_0}{m_0 \gamma}(\pm\dfrac{\chi}{a^2} + \dfrac{k^2 \Theta}{\pi}\sin\eta)\cos\varphi + Q_{self\ x,y}$.

Here $e,\ m_0$ are charge and rest mass of a particle, U_0 is intervane voltage, γ is reduced energy, $\chi = 1 - 4\Theta I_0(ka)/\pi,\ \Theta$ is effectiveness of acceleration, a is channel aperture, $k = 2\pi/L,\ L$ is modulation period, $\eta = \int k\, dz,\ \varphi = \omega\, t,\ \omega$ is angular frequency of electromagnetic field, Q_{self} is term accounting action of beam self field. For more simplicity of the problem we take as independent variable undimensional longitudinal coordinate $\zeta = z/\lambda$ instead of variable t. Here λ is the wavelength.

The equations of longitudinal motion have the form

$$\begin{cases} d\varphi/d\zeta = 2\,\pi\,\gamma\,(\gamma^2 - 1)^{-1/2}, \\ d\gamma/d\zeta = \dfrac{2\,e\,U_0 \lambda}{\pi\, m_0\, c^2} k\Theta\, \cos\eta\, \cos\varphi + F_z\ . \end{cases} \quad (4)$$

The term F_z is due to longitudinal action of self field of the beam [3]. We have also equation for η :

$$d\eta/d\zeta = 2\,\pi\,\gamma_s\,(\gamma_s^2 - 1)^{-1/2} - u_1.$$

The first component of control vector is the function u_1 such that $\int\, u_1\, d\zeta = \varphi_s - \eta$. It is the phase of synchronous particle relative to phase of spatial modulation. Another two components are $u_2 = \Theta,\ u_3 = \chi/a^2$.

For APF structure we consider the usual equations of longitudinal motion in the standing wave field. The equations of transverse motion can be taken also linear. So we can consider the analogous variables s_{11}, s_{12}, s_{22} but related to radial motion. The control function here has one component $u_1 = E_z(\zeta)$ – the longitudinal component of electromagnetic field for which can be taken various models, simplest of them being piecewise constant or piecewise linear functions.

5 THE NUMERICAL OPTIMIZATION

For solving of optimization problem formulated above we take the functional (2) with functions g and G describing the capture of the particles in transverse and longitudinal motion correspondingly. As mentioned above components of control functions were approximated by functions depending on finite number of parameters. Gradient on these parameters was calculated on the base of the expression for functional variation and method of gradient descent was applied [3]. Numerical realization included replacement of integration by summation and considering of systems (1) for discrete initial set instead of M_0.

Results of optimization are given in tab. 1,2.

6 TARGETS

Targets will be discussed briefly. Isotope C^{11} may be obtained by action of deutron beam on boron's, carbon's or nitrogen's targets. Maximal number of C^{11} (480 MBk/$\mu\mathrm{A}\cdot\mathrm{h}$ for 5 MeV) may be obtained from reaction $\mathrm{B}_5^{10}(\mathrm{d,n})\mathrm{C}_6^{11}$. If ion energy is 8 MeV, the reaction $\mathrm{N}_7^{14}(\mathrm{d,He}_2^4\mathrm{n})\mathrm{C}_6^{11}$ is the best one. It produces 311 MBk/$\mu\mathrm{A}\cdot\mathrm{h}$. Isotope N^{13} may be obtained by action of deutron beam on carbon's, nitrogen's or oxigen's targets. Carbon's target gives the best results: 2040 MBk/$\mu\mathrm{A}\cdot\mathrm{h}$ for 5 MeV beam and 8700 MBk/$\mu\mathrm{A}\cdot\mathrm{h}$ for 8 MeV one (reaction $\mathrm{C}_6^{12}(\mathrm{d,n})\mathrm{N}_7^{13}$). Isotope F^{18} may be obtained by action of deutron beam on oxigen's, fluorine's, neon's or magnesium's targets. Best results will be obtained if gas target is used. 814 MBk/$\mu\mathrm{A}\cdot\mathrm{h}$ are obtained as output reaction $\mathrm{Ne}_{10}^{20}(\mathrm{d,He}_2^4)\mathrm{F}_9^{18}$ for 8 MeV beam energy. Only reaction $\mathrm{N}_7^{14}(\mathrm{d,N})\mathrm{O}_8^{15}$ may be recommended for obtaining isotope of oxygen O^{15}. Hence minimal number of targets for obtaining four of isotopes $\mathrm{C}^{11}, \mathrm{N}^{13}, \mathrm{O}^{15}, \mathrm{F}^{18}$ are three ones. They are carbon's, neon's and nitrogen's targets. There are other possibilities. Technologies of target's fabrication for PET had developed in Russia.

7 CONCLUSION

PET-installation on base RF linac will have near the same size as PET on base cyclotron, but it will have less weight, better beam quality and radiation control.

8 REFERENCES

[1] Yu.P.Vakhrushin, M.F.Vorogushin, Yu.A.Svistunov, "RF Ion Linac for Ecology and Medicine." International Collaboration in Field of Military Conversion Technologies. St.-Petersburg. 1992, June 15-22. Report.

[2] I.M.Kapchinskij, V.A.Teplyakov. Pribory i tekhnika experimenta, N 2, p.19, 1970.

[3] D.A.Ovsyannikov, "Modeling and Optimization of Charged Particle Beam Dynamics". Leningrad State University, Leningrad, 1990.