DESIGN STUDY OF THE PROTON LINAC FOR RADIOPHARMACEUTICALS PRODUCTION

G. Kropachev, A. Balabin, D. Seleznev, and A. Sitnikov, T. Kulevoy, ITEP, Moscow, Russia

Abstract

The 8 MeV 200 MHz linac for acceleration of quasi cw 0.2 mA proton beam is under development at ITEP. The linac is designed for radiopharmaceuticals production which will be used in the Positron-Emission Tomography. The linac includes RFQ and DTL sections with 6D-beam matching between them. The DTL section has modular structure and consists of separated individually phased IH-cavities with beam focusing by permanent magnet quadrupoles located between the cavities. This DTL structure provides linac compactness and enables its tuning and commissioning cavity by cavity. Results of beam dynamic simulation and electrodynamics characteristics of linac cavities are presented.

INTRODUCTION

The 8 MeV 200 MHz linac for acceleration of 20 mA/pulse (0.2 mA average current at duty cycle 1%) proton beam is under development at ITEP. The linac is designed for radiopharmaceuticals production which will be used in the Positron-Emission Tomography. Such beam parameters provides generation of ^{18}F production and they should be obtained without activation of linac materials.

The linac consists of RFQ and DTL with 6D-beam matching between them. We proposed the modular DTL structure consisting of a number of separate individually phased accelerating cavities with beam focusing by permanent magnet quadrupoles (PMQs) located between them. The cavities are placed in the separate vacuum tanks with the identical length. PMQs can have the modular construction with constant gradient which greatly simplifies the manufacturing [9]. The linac basic parameters are shown in Table 1.

Table 1: The Linac Basic Parameters

Ions	H^+
Operating frequency	200 MHz
Beam energy	0.07÷8 MeV
Injection current	20 mA
Normalized beam emittance	0.2 π cm mrad
Normalized acceptance	0.5 π cm mrad
Transmission	> 90 %
Pulse power losses	< 1 MW
Maximum field strength	1.8 Kp
Length	~5 m

We proposed to use duoplasmatron as ion source for the linac. This ion source can provide the required beam current of 20 mA with normalized emittance lower than 0.2 π cm mrad (see Table 1).

The operating frequency equal to 200 MHz is determined by following factors:

- required acceptance (which should be higher than the beam emittance at least in 2.5 times [1]);
- accelerator compactness (the linac has to be located both in standard hospital office and in the transport unit [8]
- soft requirements to the RF structure manufacturing and adjustment.

The maximum strength of the electric field on the surface is limited by E_{smax} = 1.8* Kp = 270 kV/cm, where Kp is the Kilpatrick limit.

LINAC MAIN PARAMETRS

The layout of the medical linac and some of its parameters are given in Fig. 1. Below these parameters will be discussed.

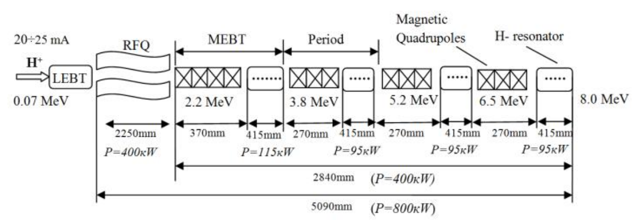

Figure 1: Layout of the medical linac.

RFQ Parameters

The RFQ consists of the matching, bunching, and regular acceleration sections. The 6D-beam matching is realized in the initial matching section. The adiabatic beam bunching is carrying out at quasi-stationary bunch mode [1]. In the regular acceleration section the protons are accelerated at constant synchronous phase of -35 degrees which achieved at intervane voltage of 147.5 kV.

To choose the injection voltage U_{inj} the following features should be taking into account. From one side to decrease the bunching section length U_{inj} should be decreased. From other side, increase of U_{inj} simplifies the vane manufacturing. The increase U_{inj} also reduces the space charge effects in the LEBT. Taking into account all these features the injection voltage U_{inj} was chosen equal to 70 kV (Fig. 1). The main RFQ parameters are presented in Table 2.

Transverse matching of continuous beam from the duoplasmatron with RFQ is realized in LEBT (Fig. 1) by two electrostatic einzel lenses with voltage ≤ 50 kV.

ISBN 978-3-95450-181-6

Table 2: The Main RFQ & DTL Design Parameters

	RFQ	DTL
Ions	H^+	
Operating frequency, MHz	200	200
Beam energy, MeV	0.070÷2.2	2.2÷8.0
Injection current, mA	20	~20
Normalized emittance, π cm mrad	0.2	~0.2
Pulse current limit, mA	200	200
Normalized acceptance, π cm mrad	0.5	0.6
Synchronous phase, deg.	-90÷-35	-35
Intervane voltage, kV	147.5	
Maximum field strength, Kp	1.8	1.8
Average radius, mm	7	
Vane radius of curvature, mm	5.6	
Maximum vane modulation	2.35	
Aperture radius, mm	18.3÷7.1÷4.2	10
Pulse RF power losses, kW	400	400
Length, m	2.25	2.84
Number of cavities	1	4
Lengths of gaps, mm		40

DTL Parameters

The necessary condition of the 6D matching between RFQ and DTL is longitudinal and transverse acceptances of the DTL not lower than the same acceptances of the RFQ. In the given linac for 6D matching between RFQ and DTL the four PMQs are used (matching quadruplet) as well as 7-gaps matching cavity which also used for beam acceleration (see Fig. 1). The electric field strength at the center of the accelerating gaps in DTL was chosen equal to 110 kV/cm, then the strength of the electric field at the DTL surface equal to 270 kV/cm which is equivalent to 1.8 Kp (Kilpatrick criteria) for resonant frequency of 200 MHz.

Focusing periods with different configuration for high acceleration gradient and required acceptance were investigated. The FDFOOOOO focusing period (Fig. 1) was chosen. Each FDFOOOOO focusing period has length of 685 mm and consists of PMQ triplet (270 mm), 5-gaps accelerating cavity (415 mm) and allows to achieve the average accelerating gradient not lower than 2 MeV/m and normalized acceptance higher than in RFQ. Total length of all three DTL focusing periods is ~2.8 m (see Fig. 1). All lenses have lengths of 70 mm and aperture radii of 15 mm. Magnetic lens gradients G are practically achievable ($G \leq 45$ T/m).

The longitudinal field distribution on axis of cavity at the first DTL period is presented in Fig. 2. The given accelerating cavity has the equal to each other length of the accelerating gaps. The electric field amplitudes in the gaps are also equal to each other except the first and the last gaps where electric field amplitude are two times lower than at center. Others periods have the same field distributions which allow to simplify cavities adjustment. Parameters of the accelerating cavities are presented in Tables 2&3.

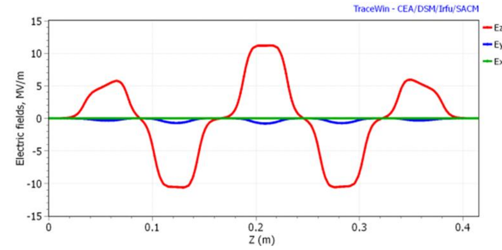

Figure 2: Distributions of the longitudinal and the transverse fields on the axis of the IH-cavity.

CHOICE OF RF STRUCTURE

According to the chosen accelerator scheme (Fig.1) the DTL should accelerate the proton beam from energy 2.2 MeV to 8 MeV (β=0.068-0.13).

The Alvarez structure has a 2π operating mode and thus it at 2 times longer compared to π- structures. Therefore the Alvarez structure was excluded from the consideration. The λ/2 & λ/4 coaxial accelerating cavities consume a high RF power, have great transverse sizes and challenge cooling systems. Such cavities are useful only under superconducting conditions [2].

The conventional IH- & CH-cavities were investigated in paper [3]. Such structures allow to achieve the acceptable accelerating gradient. These structures were compared to each other and it was found that the CH-structure consumes approximately 2 times more RF power than IH-structure [3]. Thus the IH-cavity (Fig. 3) was chosen for the DTL. This cavity is cheap and easily adjustable. The main parameters of IH-cavity are presented in Table 3.

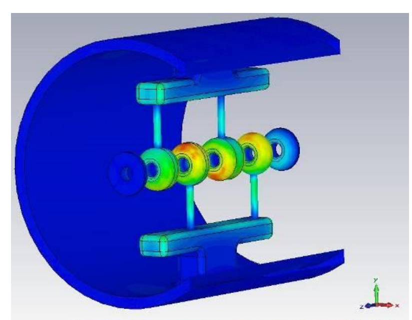

Figure 3: IH-cavity and electric field distribution

Table 3: Main Parameters of 5-gap IH-cavity

Resonant frequency	200 MHz
Field strength in accelerating gaps	110 kV/cm
Quality factor	8400
Maximum field strength	266 kV/cm
Pulse RF power losses	95 kW
Length	0.415 m
Diameter	0.3 m

The IH-cavity disadvantage is a transverse electric field on the axis [4]. The longitudinal E_z (accelerating) and

ISBN 978-3-95450-181-6

transverse E_y (deflecting) electric field distributions on axis are presented in Fig. 2.

The E_{ymax} (the maximum value of the transverse electric field on the cavity axis) can reach up to 5-10% to E_{zmax} (the maximum value of the longitudinal electric field on the cavity axis) and depends on cavity design. Since the IH-cavity operates on π mode the transverse electric field on the cavity axis has an opposite direction in time at each accelerating gap. Therefore the transverse electric field influence on the beam is mostly compensated.

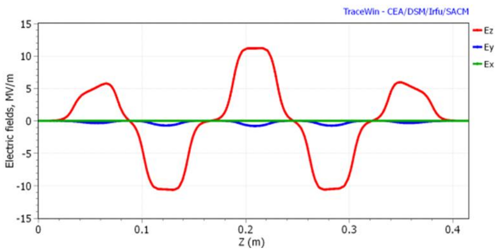

Figure 3: Distributions of the longitudinal and the transverse fields on the axis of the IH-cavity.

NUMERICAL SIMULATION OF BEAM DYNAMICS IN THE LINAC

Numerical simulation of the beam dynamics in the medical linac was carried out by macro particles method using RFQDYN, DYNAMION [4], and LIDOS [5] codes. Graphical representation of simulation results is performed by PlotWin code [6].

The beam transmission in the RFQ is equal to 95% for injection current of 20 mA .

The results of end-to-end particles dynamics simulation in the linac are presented in Fig. 4. As seen from Fig. 4 the rms-envelopes have a periodic character with increased up to 2 times the transverse beam sizes in the DTL compared to beam sizes in the RFQ. It should be mentioned that the aperture size in the DTL is larger up to 2.4 times than the RFQ.

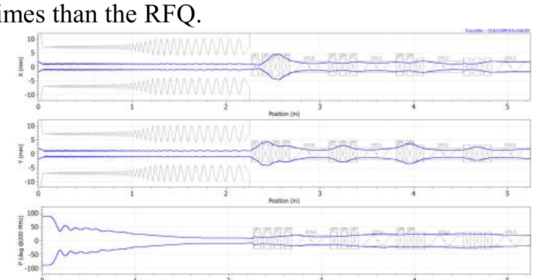

Figure 4: Rms-envelopes of the beam in the linac.

The phase spaces for accelerated 20 mA proton beam at DTL output are presented in Fig. 5. Particle losses in DTL are negligible and total transmission is about 95%. The emittance growth at RFQ & DTL less than 20 %.

The particles dynamics simulation with transverse electric field (deflecting) on the axis was carried out. The simulation shows that the transmission is reduced by 0.5% while emittance is increased by 5%. According to that the transverse electric field has no influence on beam dynamics in this case.

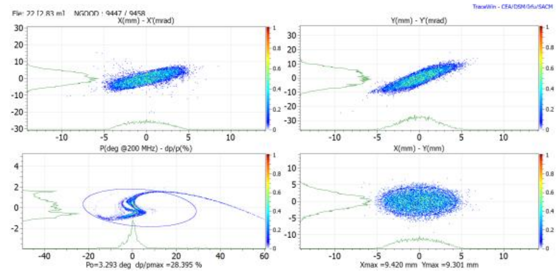

Figure 5: Phase spaces at the DTL output.

CONCLUSION

The scheme of the medical linac (Fig.1) consisting of RFQ and DTL including a number of separate individually phased accelerating cavities with beam focusing by PMQs is proposed.

The linac provides a high particle transmission about 95% for proton injection current of 20 mA. The PMQs minimize the electric power consumption. Magnetic lens gradients are practically achievable for the permanent magnet assembly. PMQs can have the modular construction with constant gradient which greatly simplifies the manufacturing.

The complexity of the DTL supply system by individual RF generators is compensated by simplicity of fabrication and tuning of cavities. The modular DTL structure is flexible and allows tuning and commissioning section by section. Moreover the modular structure can be used for other applications such as BNCT, neutron generator, semiconductor industry etc. The proposed scheme of the medical linac can be used as a base for a serial compact accelerator production.

REFERENCES

[1] I. M. Kapchinskij, Theory of Resonance Linear Accelerators, Harwood, 1985.

[2] S. Kurennoy, J. O'Hara, L. Rybarcyk, «Compact Linac for Deuterons (Based on IH Structures with PMQ Focusing)» HB 2008, August 27,2008 LANL, Los Alamos.

[3] S.S. Kurennoy, L.J. Rybarcyk, and T.P. Wangler, «AN H-MODE ACCELERATOR WITH PMQ FOCUSING AS A LANSCE DTL REPLACEMENT». Proceedings of IPAC2011, San Sebastián, Spain WEPS067 LANL, Los Alamos, NM 87545, U.S.A.

[4] V. Andreev, N.N. Alexeev, A. Kolomiets, V. Koshelev, A. Plastun, «NOVEL DTL SECTION FOR ITEP-TWAC HEAVY ION INJECTOR» Proceedings of RUPAC2012, Saint|-|Petersburg, Russia WEPPC013

[5] A.Kolomiets, et al., DYNAMION – The code for beam dynamics simulation in high current ion linac, Proc. Of EPAC-98, Stockholm, Sweden, 1998, pp. 1201-1203.

[6] B.I.Bondarev, A.P.Durkin, et al. LIDOS Unconventional, Helper for Linac Beam Designing. Computational Accelerator Physics Conference, AIP, Conference Proceedings 297, Los Alamos, NM 1993, pp.377-384.

[7] http://irfu.cea.fr/Sacm/logiciels/

[8] Pulsar TM 7 PET Isotope Production System, AccSys Technology, inc.

[9] V.S. Skachkov et al. RSI 87,023303 (2016)

ISBN 978-3-95450-181-6