DTL cavity design and beam dynamics for a TAC linear proton accelerator*

A. Caliskan[1)] M. Yılmaz[2)]

Gazi University, Arts and Sciences Faculty, 06500 Besevler, Ankara, Turkey

Abstract: A 30 mA drift tube linac (DTL) accelerator has been designed using SUPERFISH code in the energy range of 3–55 MeV in the framework of the Turkish Accelerator Center (TAC) project. Optimization criteria in cavity design are effective shunt impedance (ZTT), transit-time factor and electrical breakdown limit. In geometrical optimization we have aimed to increase the energy gain in each RF gap of the DTL cells by maximizing the effective shunt impedance (ZTT) and the transit-time factor. Beam dynamics studies of the DTL accelerator have been performed using beam dynamics simulation codes of PATH and PARMILA. The results of both codes have been compared. In the beam dynamical studies, the rms values of beam emittance have been taken into account and a low emittance growth in both x and y directions has been attempted.

Key words: proton accelerator, cavity design, beam dynamics

PACS: 29.20.Ej **DOI:** 10.1088/1674-1137/36/2/012

1 Introduction

The Turkish Accelerator Center (TAC) project aims to give a regional facility for an accelerator based on fundamental and applied research [1, 2]. Its conceptual design report was completed in 2005. The TAC project will include the design of a linac-ring type electron-positron collider for a charm factory and a 1 GeV energy proton linac. It will also include the design of a linac based free electron laser and a ring based third generation synchrotron radiation source. The linear proton accelerator will give an opportunity to produce secondary muon and neutron beams for applied research fields. In the muon region, a lot of applied investigations into high-T_c superconductivity, phase transitions, impurities in semiconductors will be performed using the powerful Muon Spin Resonance (μSR) method. In the neutron region, it is planned to search for the different fields of science such as engineering, molecular biology and fundamental physics.

The main components of the linear proton accelerator are an ion source (H^-), a Radio-Frequency Quadrupole (RFQ), a Drift Tube Linac (DTL), a Coupled-Cavity Drift Tube Linac (CCDTL) and a Coupled-Cavity Linac (CCL) [3, 4]. There is a Low Energy Beam Transport channel between the ion source and the RFQ. Its task is to match the ion beam to the RFQ. While the beam obtained from the ion source is in the continuous mode, the conversion of the ion beam to the pulsed structure is realized in the RFQ structure. The acceleration, the focusing and the bunching of the ion beam are simultaneously performed in the RFQ. Only transverse electric fields are used in the RFQ for these processes. Axial longitudinal electric fields for the beam acceleration process are produced by internal surface modulation of the electrodes in the RFQ. There is no acceleration in the first section of the RFQ structure called the Radial Matching Section [5]. After the beam is converted into the bunched structure, acceleration to an energy of 3 MeV starts. The second transport section of the proton accelerator is between the RFQ and the DTL. In this channel, called Medium Energy Beam Transport, the beam chopping process and the matching to the DTL are performed. Quadrupole magnets are

Received 7 June 2011

∗ Supported by Turkish State Planning Organization (DPT) (DPT-2006K120470)

1) E-mail: a.caliskan@gazi.edu.tr

2) E-mail: metiny@gazi.edu.tr

used for matching to the DTL.

In this study, a 30 mA DTL with a 350 MHz operating frequency has been designed. The DTL structure is an Alvarez-type accelerator and used in many modern linear proton accelerators including spallation neutron sources. The DTL accelerates the ion beam from 3 MeV to 55 MeV using three accelerator tanks. The cell design of the DTL cavities has been made with DTLfish from the SUPERFISH code group [6–8] and we have used the codes of the PARMILA and the PATH for the whole linac design and beam dynamics.

2 DTL cell design

The code group of the SUPERFISH is an electromagnetic field solver and there are appropriate codes in this group for different linear accelerator structures such as the RFQ, the DTL, the CCDTL and the CCL [9]. We have used the DTLfish from this group for the DTL design. The cell geometry used in the program is shown in Fig. 1. In this figure, ten important geometrical parameters are shown. These parameters are the tank diameter (D), the cell length (L), the drift tube diameter (d), the gap length (g), the bore radius (R_{b}), the drift tube face angle (α_{f}), the drift tube corner radius (R_{c}), the drift tube inner nose radius (R_{i}), the drift tube outer nose radius (R_0) and the drift tube flat length (F). A cell starts from the middle of the drift tube and ends in the middle of the next drift tube in this cell geometry. As the speed of particles increases, the lengths of drift tube and gap grow longer along the accelerator because of the synchronization condition between the beam and the RF voltage. The length of the cell is chosen equal to $n\beta\lambda$ to satisfy this condition, where n is an integer and λ is the wavelength of the RF voltage. The electric field intensity is very high compared with the other areas of the tank in the small gap regions between the drift tubes.

Since the space charge forces at low energies dominate the beam, quadrupole magnets providing strong focusing in the x and y directions are needed. There must be enough room to install the magnets inside the drift tubes because the quadrupole magnets are placed inside the drift tubes. This situation brings a limitation to the choice of drift tube diameter, d.

Since the DTLfish generates geometrically symmetrical cells, it simulates a quarter of the DTL cell by adjusting the cavity diameter, the face angle, the drift tube diameter or the gap up to achieve a recognized resonant frequency. We have used the gap tuning option in our simulations. The geometrical parameters of the DTL cell have been varied in order to optimize the effective shunt impedance and the transit time factor of the cavity in the optimization

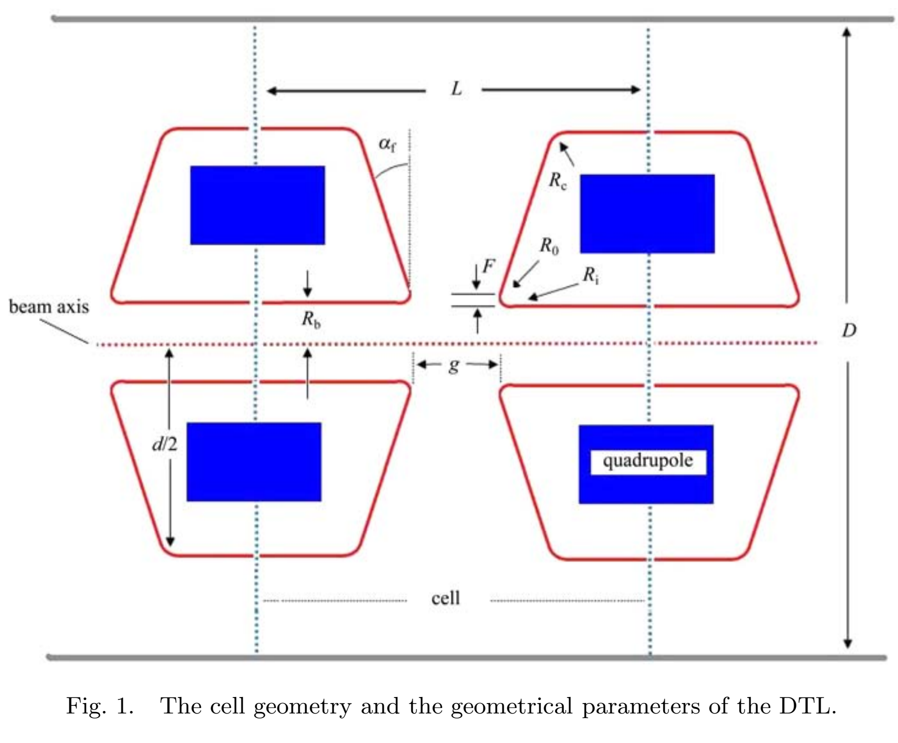

Fig. 1. The cell geometry and the geometrical parameters of the DTL.

process. The parameter of the effective shunt impedance is the multiplication of the shunt impedance with the transit time factor and it measures the amount of accelerating field per unit power expended in the walls of the cavity. High values of the transit time factor increase the energy gain of particles in the gap regions. At the end of the optimization process, we have found that $D=54$ cm, $R_{\mathrm{b}}=10$ mm, $D_{\mathrm{s}}=26$ mm ($D_{\mathrm{s}}=$ stem diameter), $d=80$ mm, $R_{\mathrm{c}}=60$ mm, $\alpha_{\mathrm{f}}=3°$, $F=0$, $R_{\mathrm{i}}=15$ mm and $R_0=15$ mm.

3 Main linac design

The DTL accelerator is expected to consist of three tanks. We have formed a cell geometry only for Tank 1 in the previous section. The same basic geometrical cell parameters determined in the former section have been chosen for Tank 2 and Tank 3 to avoid complexity of geometry. Only one parameter in Tank 2 is different from the other tanks. This is the face angle and it varies along Tank 2 to increase the effective shunt impedance (ZTT) advance. The face angle increases linearly from $\alpha_{\mathrm{f}}=3°$ to $\alpha_{\mathrm{f}}=26°$ between $\beta=0.165$ and $\beta=0.225$ and it is kept constant from $\beta=0.225$ to $\beta=0.25$. Fig. 2 shows the effective shunt impedance graph. According to this graph, the ZTT has a maximum at about 25 MeV in Tank 2 and later it decreases continuously. We will pass to the CCDTL structure in the next study to keep the high acceleration efficiency after 55 MeV. The effective shunt impedance graph also shows that this DTL accelerator design is quite efficient.

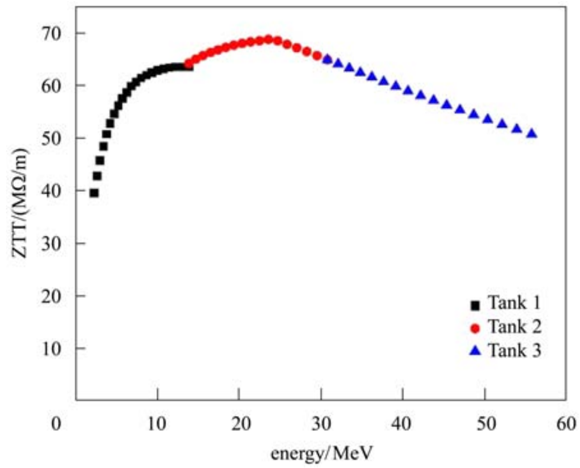

Fig. 2. Effective shunt impedance graph of the DTL consisting of three tanks.

We have used the PARMILA code [10] for the whole linac design where SFDATA tables from the DTLfish are needed. The program of the PARMILA can simulate both the linac design and the beam dynamics. The PARMILA forms the linac geometry after some parameters are entered as an input file. The averaged axial electric field, E_0, is a very important parameter in the linac design because it affects the linac length directly. It defines the amount of voltage per unit length and uses 3.2 MV/m for Tank 1, 3.3 MV/m for Tank 2 and 3.4 MV/m for Tank 3 in our calculations. Another important parameter is the maximum surface electric field on the drift tubes which is expressed using the Kilpatrick factor. The linac must be operated below a Kilpatrick factor of 2

Table 1. Linac parameters of the DTL for each tank.

parameters	Tank 1	Tank 2	Tank 3
frequency/MHz	350	350	350
energy range/MeV	3–13.24	13.24–30.84	30.84–55.66
gradient E_0/(MV/m)	3.2	3.3	3.4
synchronous phase/(°)	−30/−20	−20	−20
number of cells	41	37	39
number of gaps	41	37	39
max surface field [kilp.]	1.01/1.39	1.00/1.38	1.29/1.38
tank length/m	4.26	6.60	9.72
quadrupole length/cm	4	6	8
quadrupole gradient/(T/m)	53.3/56	44.7	34.5
quadrupole lattice	FFDD	FFDD	FFDD
aperture radius/mm	10	10	10
transit-time factor	0.76–0.84	0.84–0.86	0.74–0.84
peak RF power/MW	0.81	1.32	1.99
copper RF power/MW	0.51	0.79	1.25

to avoid electrical breakdown. It is a function of the RF frequency. Its value is 18.39 MV/m for 350 MHz. Table 1 shows the general linac parameters. As seen from this table, all values of Kilpatrick factor are below 1.4, which shows that this is a quite conservative design.

4 Beam dynamics simulation

The beam dynamics design of the DTL accelerator has been performed with 100000 macroparticles using the codes of the PATH [11] and the PARMILA. A 30 mA Gaussian beam with normalized transverse rms emittance of 0.276 π mm·mrad has been generated for input to the DTL. Table 2 shows the normalized beam parameters of the input and the output beam distributions. The lengths, the gradients and the lattice of the quadrupole magnets have been determined in the simulations. The quadrupole magnet lattice indicating the focusing and defocusing order of a magnet has first been investigated on the condition that the accelerator has not lost any particles. Only an FFDD lattice, after trying a number of different lattices, has been appropriately provided where the first drift tube of Tank 1 is empty. There are forty quadrupoles in Tank 1, thirty-seven quadrupoles in Tank 2 and thirty-nine quadrupoles in Tank 3. We have again used quadrupole magnets to continue the FFDD lattice from the last cell of the first tank to the first cell of the next tank in the space between the tanks. Magnet lengths in a limited area calculated by the PARMILA and the quadrupole gradients have been tuned with the PATH at a specified interval to get low emittance growth without any particle loss.

Table 2. Normalized twiss parameters at the input and output of the DTL accelerator for real current.

space	parameters	input	output	unit
x-x'	rms emittance	0.276	0.396	mm·mrad
	α	2.8699	−2.8608	
	β	4.4998	3.3601	m/rad
y-y'	rms emittance	0.265	0.308	mm·mrad
	α	−2.3799	2.0668	
	β	2.1249	1.8178	m/rad

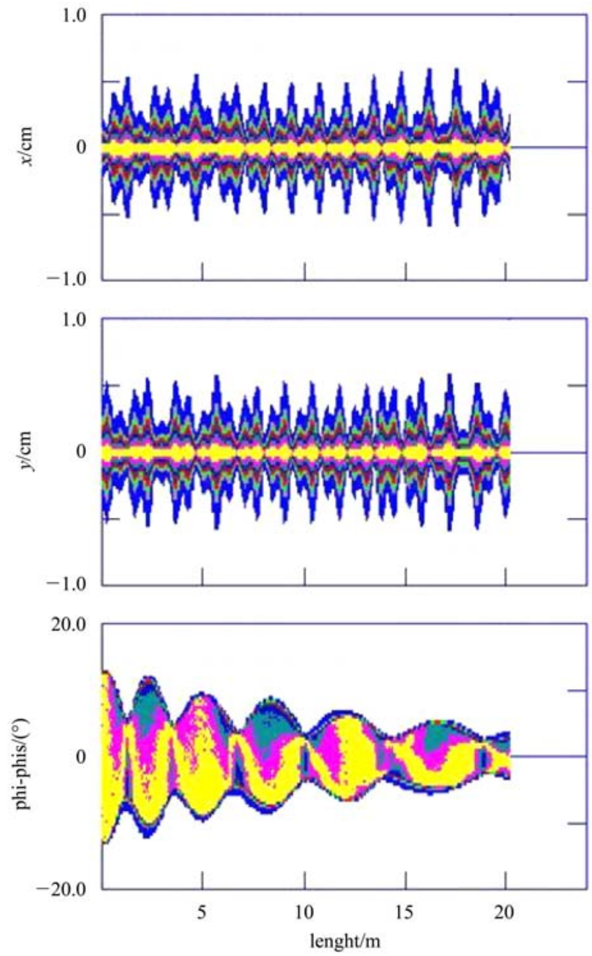

Fig. 3. The x-beam profile (top), y-beam profile (medium) and phase advance (bottom) of ion beam for zero-current.

The beam dynamics simulations are performed without any particle loss as shown in Fig. 3. According to the x and y beam profiles in this figure, the beam envelope in both directions remains within a border of 1 cm and progress is smooth. The graph of phase advance shows that the phase envelope is initially bigger but later it gradually decreases. The phase envelope of the betatron motion of particles in the beam is smaller at the end. As a result, the beam structure at the exit of the DTL accelerator is more stable than that at the entrance. The results of the beam dynamics of both codes reasonably agree with each other as shown in Figs. 4, 5 and 6.

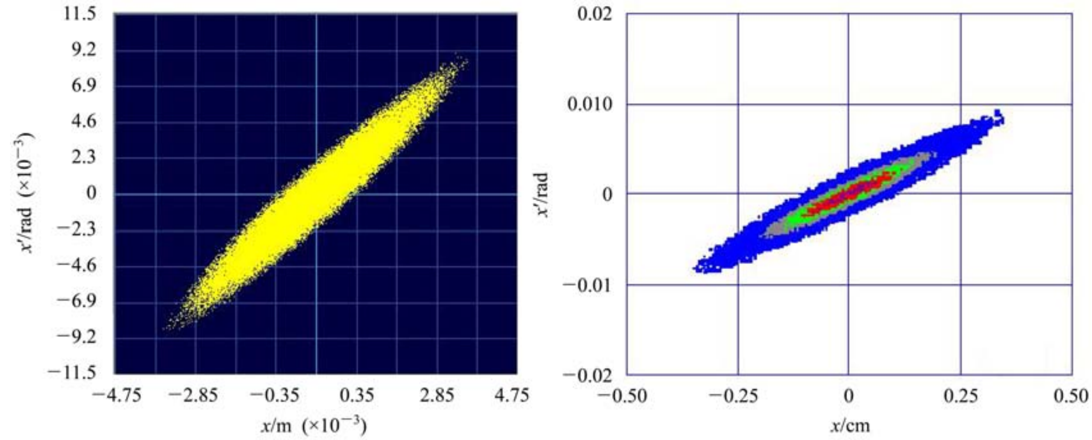

Fig. 4. Emittance in x-x' space of the exit beam for the PATH (left) and the PARMILA (right).

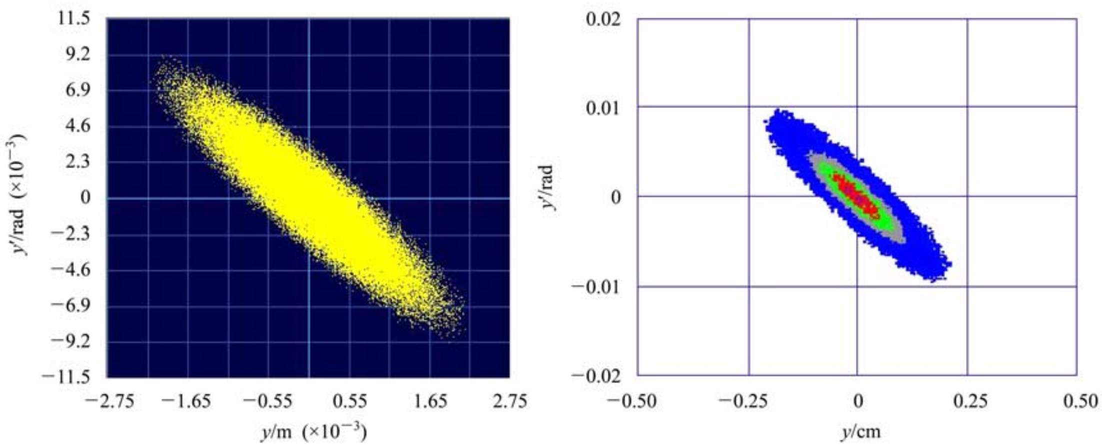

Fig. 5. Emittance in y-y' space of the exit beam for both codes.

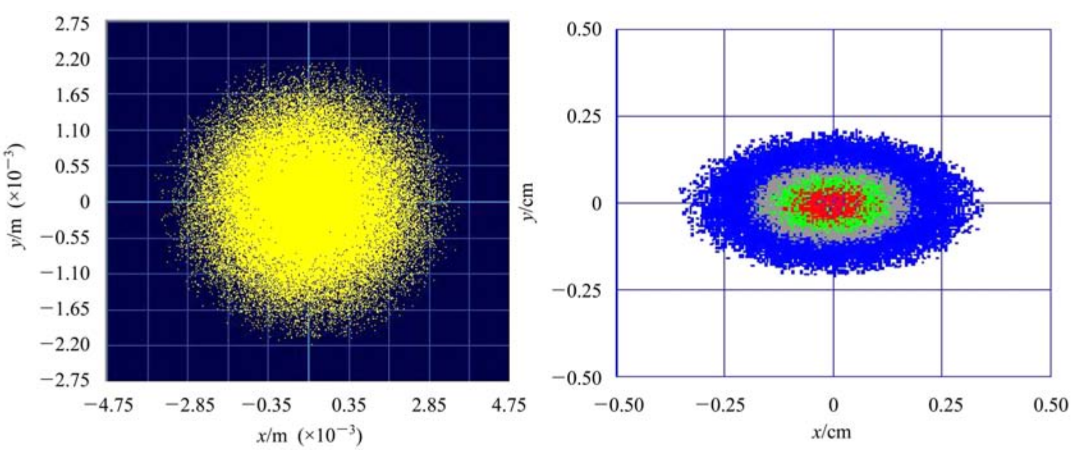

Fig. 6. Beam view in x-y real space of the exit beam for both codes.

We want to get low emittance growth in the simulation studies. As seen in Fig. 7 which is for zero-current, the transverse normalized emittance in x-x' space increases in Tank 1 and remains constant along Tank 3. According to the simulation results, the emittance increases by 1.067% in Tank 1, decreases by 0.207% in Tank 2 and decreases by 0.093% in Tank 3 for zero-current simulations. We have simulated different beam currents to take into account the space charge effects. Fig. 8 shows the emittance growth for the currents of 10 mA, 30 mA and 50 mA. While the beam current strength increases, the emittance growth also increases. The real current value of the DTL is 30 mA.

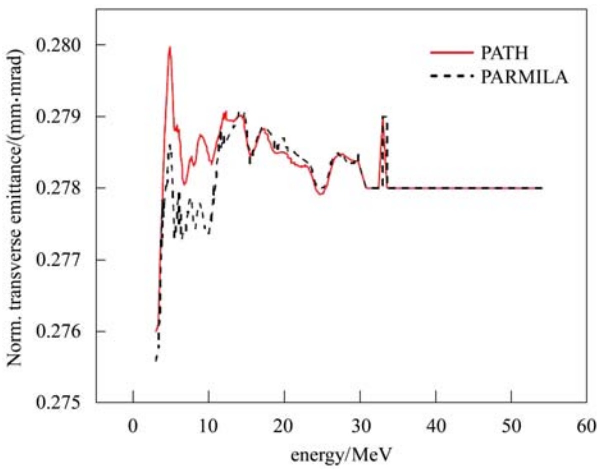

Fig. 7. Emittance growth for both codes from zero-current simulations.

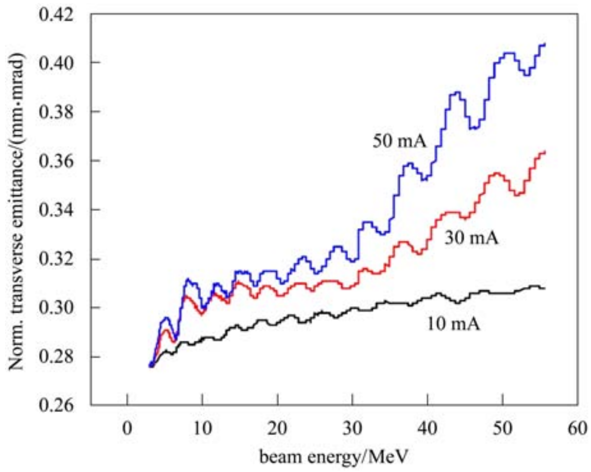

Fig. 8. Emittance growth along the DTL for the beam currents of 10 mA, 30 mA and 50 mA respectively.

5 Conclusions

We have designed a DTL accelerator consisting of three tanks. The cell design of the DTL has been simulated by using the DTLfish code. Geometrical parameters of the cell have been optimized by tuning the gap lengths of the cavity to obtain maximum effective shunt impedance and transit time factor. Geometrical parameters are the same for the three tanks. The only parameter which changes along the accelerator is the face angle in Tank 2. The design of the cavity is quite conservative from the electrical breakdown because the Kilpatrick factor along the whole accelerator is below 1.4. The effective shunt impedance graph shows that the designed DTL covering an energy range of 3–55 MeV is an efficient accelerator and it can be used for any project with these parameters. The total length of the DTL is about 20.5 m. The number of quadrupole magnets is 118 which includes the magnets between tanks. The beam dynamics simulations have been performed using the PATH and the PARMILA with 100000 macroparticles to obtain low emittance growth. The results of simulations are the same for both codes. The overall results from this study demonstrate that the DTL accelerates the ion beam from 3 MeV to 55 MeV with these parameters without particle loss and a quite stable ion beam can be obtained with low emittance growth.

The authors would like to thank Alessandra M. LOMBARDI from CERN for support of code and Saleh SULTANSOY for valuable contributions.

References

1 Sultansoy S, Yilmaz M, Cakır O, Ciftci A K, Recepoglu E, Yavas O. The Status of Turkic Accelerator Complex Proposal, Proceedings of the Particle Accelerator Conference (PAC05). Knoxville, Tennessee, USA. 2005, 449–551
2 Turkish Accelerator Center web page: http://thm.ankara.edu.tr
3 Algin E,Akkus B, Calıskan A, Sahin L, Yilmaz M. TAC Proton Accelerator Facility: The Status and Road Map, Second International Ulaanbaatar Conference on Nuclear Physics and Applications (UBC2010). Ulaanbaatar, Mongolia. 2010
4 Arnaudon L, Baylac M et al. Linac4 Technical Design Report, CERN-AB Department, CERN-AB-2006-084 ABP/RF. Geneva, Switzerland, 2006
5 Young L. 25 Years of Technical Advances in RFQ Accelerators, Proceedings of the 2003 Particle Accelerator Conference, Portland, USA, 2003
6 Ungrin J, Michel W L. Nucl. Instrum. Methods Phys. Res., Sect. A, 1985, **240**: 6
7 Caliskan A, Yilmaz M. Balkan Physics Letters, 2009, **18**(181002): 8–15
8 Caliskan A, Kisoglu H F, Yilmaz M. Azerbaijan Journal of Pyhsics, 2010, **XVI**(2): 534–536
9 Bilen J H, Young L M. Poisson Superfish, Los Alamos National Laboratory document, LA-UR-96-1834, Rev. 2005
10 Takeda H, Parmila. Los Alamos National Laboratory document, LA-UR-98-4478, Rev. 2005
11 Perrin A, Amand J F, Mutze T, Lallement J B. Travel User Manuel. CERN, 2007