Beam dynamics design and electromagnetic analysis of 3 MeV RFQ for TAC Proton Linac*

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(Received May 30, 2014; accepted in revised form September 11, 2014; published online June 20, 2015)

A beam dynamics design of 352.2 MHz radio-frequency quadrupole (RFQ) of Turkish Accelerator Center (TAC) project which accelerates continuous wave (CW) proton beam with 30 mA current from 50 keV to 3 MeV kinetic energy has been performed in this study. Also, it includes error analysis of the RFQ, in which some fluctuations have been introduced to input beam parameters to see how the output beam parameters are affected, two-dimensional (2-D) and three-dimensional (3-D) electromagnetic structural design of the RFQ to obtain optimum cavity paramaters that agree with the ones of the beam dynamics. The beam dynamics and error analysis of the RFQ have been done by using LIDOS.RFQ. Electromagnetic design parameters have been obtained by using SUPERFISH for 2-D cavity geometry and CST Microwave Studio for 3-D cavity geometry.

Keywords: Radio-frequency quadrupole, CW beam, Proton, Beam dynamics

DOI: 10.13538/j.1001-8042/nst.26.030103

I. INTRODUCTION

The Turkish Accelerator Center (TAC) project [1] was approved by Turkish State Planning Organization (DPT) in 2006. The project includes an infrared free electron laser (IR-FEL) & bremstrahlung facility, a particle factory, a third generation synchrotron radiation facility, a self-amplified spontaneous emission (SASE) mode free electron laser and a GeV scale linear proton accelerator (proton linac) facility, being developed by collaboration of more than 10 Turkish universities [2].

The envisaged proton linac will accelerate proton beams up to 2 GeV and serve as a source of effective uses for users in many industrial, technical and health service areas. It will also provide opportunity of research in nuclear science and high energy physics. The primary objective is usage of this linac in energy generation based on accelerator driven systems (ADS) technology in view of thorium reserves of Turkey [3].

The proposed linac will consist of a low-energy section of ∼3 MeV, a medium-energy section of ∼250 MeV and a high-energy section of ∼2 GeV with superconducting cavities (Fig. 1). The low-energy section, front-end of the linac, will be composed of a microwave-off resonance type ion source, a low energy beam transport (LEBT) line that transports and matches the beam from the source with a radio-frequency quadrupole (RFQ), which is "sine qua non" for today's heavy ion linacs [4].

In this paper, we focus on beam dynamics of the design, the error analysis and electromagnetic structural design of RFQ. The design specifications of the RFQ are given in Table 1.

We have used an input beam with a current of 30 mA for beam dynamics of the RFQ in accordance with the latest feasibility studies. A four-vane type RFQ has been chosen pursuant to 352.2 MHz radio-frequency. Also, continuous wave (CW) beam has been envisaged to meet the need of various applications. So the power consumptions must be tackled cautiously. In this paper, beam dynamics and error anaylsis of the RFQ are simulated using LIDOS.RFQ [5]. Electromagnetic structural design parameters are obtained by using SUPERFISH [6] for 2-D cavity geometry and CST Microwave Studio [7] for 3-D cavity geometry.

TABLE 1. Design specifications of the RFQ

Parameters	Value
RFQ type	4-vane
Frequency (MHz)	352.2
Duty cycle (CW)	100%
Particle	Proton
Beam current (mA)	30
Input energy (keV)	50
Output energy (MeV)	3

II. BEAM DYNAMICS DESIGN OF THE RFQ

The RFQ design studies based on beam dynamics simulation are performed to optimize beam dynamics parameters in compliance with given conditions such as operating RF frequency, intervane voltage, input beam current, kinetic energy, emittance, etc. Desired energy and beam current at the RFQ exit must be achieved using the parameters obtained from the beam dynamics design. Minimum emittance growth, compactness of the RFQ and maximum beam transmission are also required for the beam dynamics design of RFQ.

Emittance (normalized, rms) of the input beam was chosen as $0.20\,\pi$ mm mrad . The input energy should be selected as low as space-charge forces permit to get more compact structure. The initial particle distribution was chosen as 4-D uniform with 10 000 particles.

Some beam dynamics parameters were tuned using

* Supported by the Turkish State Planning Organization (DPT) (No. DPT-2006K120470)

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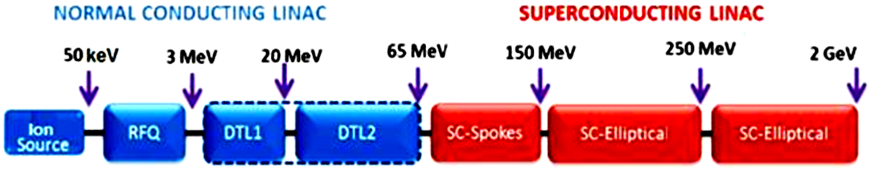

Fig. 1. (Color online) Block diagram of the TAC proton linac.

LIDOS.RFQ software taking into account space-charge effects. Evolution of the modulation parameter (m), synchronous phase (Φ_s), minimum aperture (a), acceleration efficiency (A), kinetic energy (W) and intervane voltage (U_0) in consequence of the optimization are shown in Fig. 2.

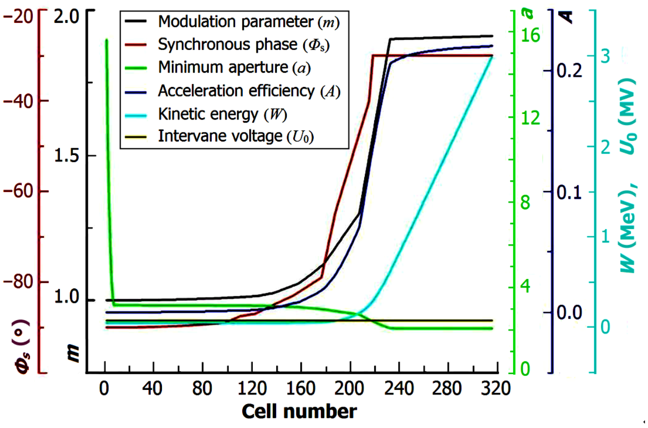

Fig. 2. (Color online) Evolution of some beam dynamics parameters along the RFQ in consequence of the optimization.

RFQ structure is divided into four sections in conventional design methods. One of these is "Radial Matching Section (RMS)" that adapts CW beam to time-varying structure of RFQ. We have reserved 7 cells, each of 0.44 cm in length, for RMS in our design. The structure consists of 316 cells which make a length of 3.45 m in total. As shown in Fig. 2, minimum aperture, (a), from the z-beam axis goes down from a maximum value of 15.6 mm to the average bore radius (r_0) of 3.17 mm in the RMS. In this section, the m is 1, hence no modulation, and Φ_s is $-90°$. This means that there is no acceleration while focusing is maximized in this section. Thus, the beam is not formed into bunches and the bucket has the maximum length [8].

"Shaper" section comes after RMS downstream of the beam. This section regulates the parameters as required by "Gentle Buncher (GB)" section which follows the shaper. The 116 cells in the shaper give the beam a small acceleration since m rises up to 1.015. There is still focusing although not as much as that of RMS. The Φ_s varies from $-90°$ to $-86.7°$ resulting in a longitudinal shrinkage in the bucket. Also, A, acceleration efficiency gently increases from 0 to 0.004 as a result of small acceleration and there is an increment of 0.30 keV on kinetic energy, W, at the end of this section, according to Fig. 2.

Bunching process mainly occurs in GB section in an RFQ. This is carried out by keeping the charge density nearly constant so as to reduce the space charge effects. In this section, parameters, such as m, Φ_s, A, rise faster than those of other sections because of bunching. In our design, GB consists of 109 cells. At the end of this section, m and Φ_s have values of 1.90 and $-30°$, respectively. A is 0.41 whereas a is 2.09 mm in compliance with inverse proportionality to m. W is 0.62 MeV as shown in Fig. 2.

In the last section, which is named "Acceleration Section (AS)", there are 83 cells and m, a and Φ_s are nearly constant. Hence, focusing is almost steady for keeping the A high so as to reach desired energy at the end of the RFQ. So, W is 2.99 MeV and A is 0.44 whereas m and Φ_s are 1.911 and $-30°$, respectively.

Last cell of the RFQ is generally used as a "transition cell" to end the RFQ with quadrupolar symmetry. There is no axial potential, hence, accelerating field in this cell and it makes possible to control the orientation of the ellipse in transverse phase-space. There is a "fringe field" at the end of this cell used for matching the output beam with the next accelerator structure. A transition cell with a length of 33.98 mm has been used in our design.

From Fig. 2, the intervane voltage has been chosen as constant along the whole RFQ structure. We have taken the average bore radius and transverse radius of curvature of vane tip, ρ, as constant. Thus, capacitance of the vanes is invariant and fabrication becomes easier. This makes a contribution to flatness of, E_z, accelerating electric field for the purpose of prevention of particle losses, and to the error analysis without complexity. One of the important factors in determining the intervane voltage is Kilpatrick Criterion [9]. We have chosen a limitation of 1.8 times this criterion considering the CW beam used. An intervane voltage of 76.80 kV has been kept constant along the RFQ structure. The design parameters obtained from simulation are given in Table 2.

From Table 2, maximum electric field is 31.62 MV/m in accordance with 1.8 Kilpatrick limit, i.e., 33 MV/m. About 97% of all particles are transmitted and 98.5% of these particles are captured for acceleration. A portion of 86 kW of total RF power requirement of 526 kW is delivered to the beam while 440 kW is dissipated on the structure walls. This value 1.7 times that of SUPERFISH. Unaccelerated beam portion of 1.5% has a power of 0.146 kW which is negligible compared to 86 kW. Emittance growth, another figure of merit, is 15% according to Table 2. The beam has a longitudinal emittance of 0.087 π deg MeV at the exit of the RFQ, as an indication of existence of bunching. Brightness of the beam,

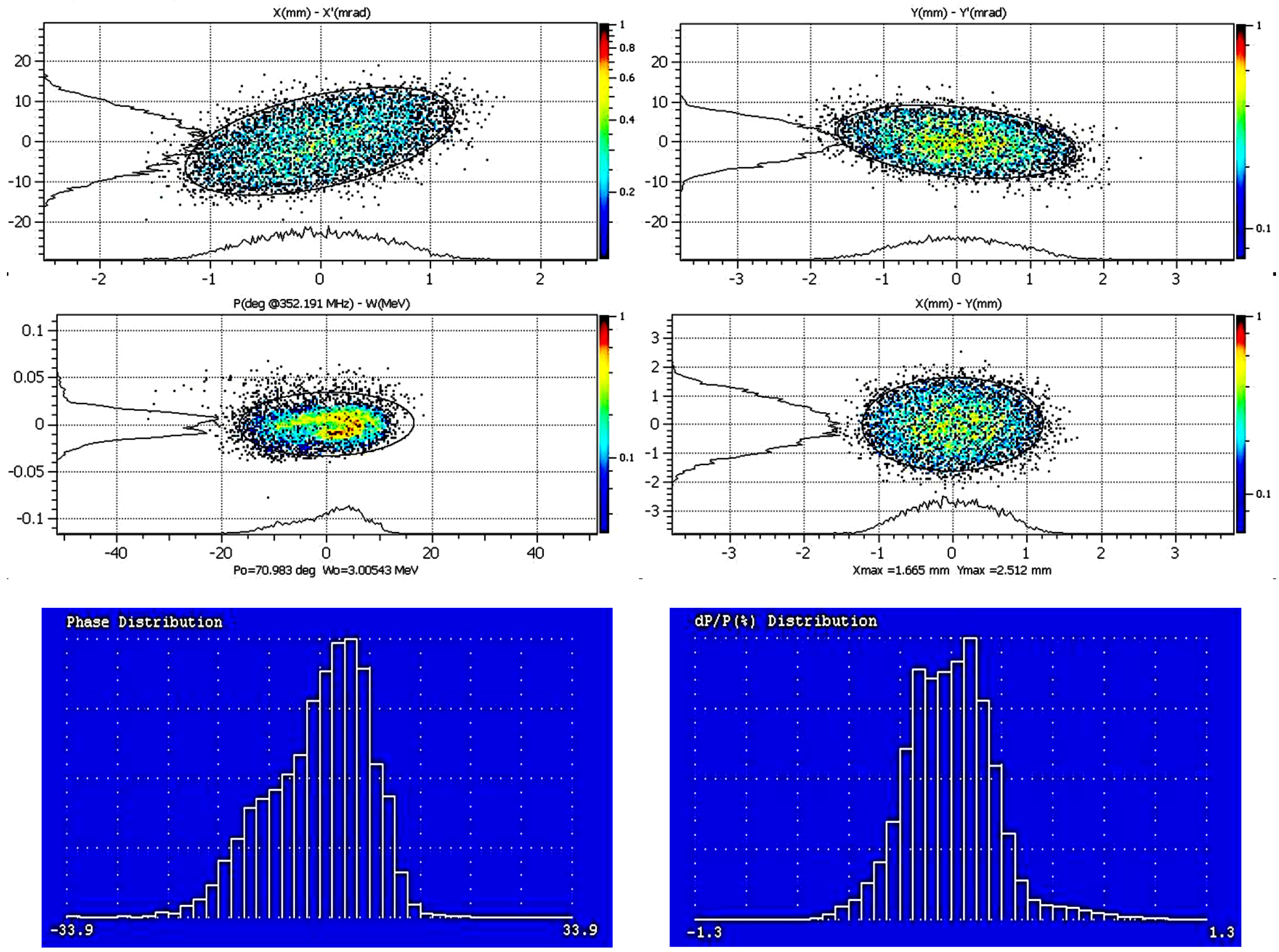

Fig. 3. (Color online) Beam profile (a) and phase and energy distribution of the beam particles (b) at the RFQ exit.

TABLE 2. Design parameters of the RFQ

Parameters	Value
Intervane voltage, U_0 (kV)	76.8
Modulation parameter, m	1 – 1.911
Average bore radius, r_0 (mm)	3.17
ρ/r_0	0.85
Synchronous phase, Φ_s (°)	-90 to -30
Maximum surface electric field (MV/m)	31.62 (1.8 Kilpatrick)
Transmission	96.9%
Beam power (kW)	86
Power dissipation (1.7 × SUPERFISH) (kW)	440
Total length (without both ends) (m)	3.45
Input emittance (norm., rms), $\varepsilon_{x,y}$ (π mm mrad)	0.20
Output emittance (norm., rms), ε_x (π mm mrad)	0.23
ε_y (π mm mrad)	0.23
ε_z (π deg MeV)	0.087

defined as $B = I/(\varepsilon_x\varepsilon_y)$ [10], is a main figure of merit. The beam brightness is 549.5 mA/(π^2 mm^2 mrad^2), referring to Table 2. The output beam profile is shown in Fig. 3

III. ERROR STUDY OF BEAM PARAMETERS

In error analysis of the RFQ, we applied some variations on the input beam parameters to see how the output beam parameters are affected. Transmission and capture (i.e., accelerated particles) efficiencies were figures of merit in this analysis. We checked over the effects of fluctuations in input beam current, input emittance, input energy and intervane voltage on transmission and capture efficiencies by using LIDOS.RFQ. The results are shown in Fig. 4.

In error study simulations, 95% transmission and capture have been chosen as lower acceptability limit. According to this, an input beam current in the range of 10–40 mA is acceptable, referring to the Fig. 4, considering that the other parameters are invariant. Input beam energy from 49.5–52.2 keV is bearable and input emittance from $\sim$ 0.07 π mm mrad to $\sim$ 0.37 π mm mrad can be tolerated. Besides these, the RFQ works properly if the intervane voltage is started to increase from 75.3 kV (U/U_0 = 0.98), although operating voltage is 76.8 kV, paying attention to the Kilpatrick Criterion.

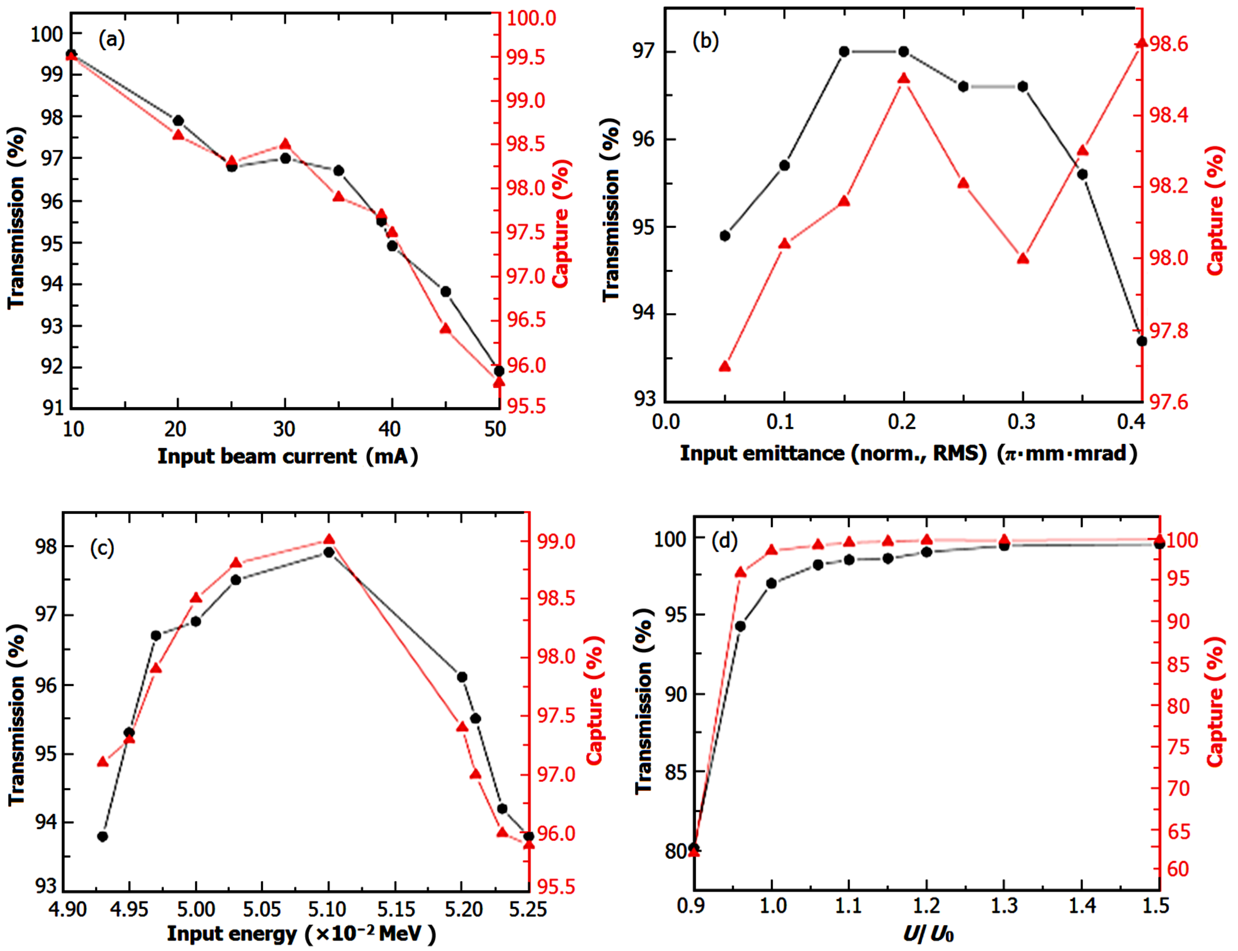

Fig. 4. (Color online) Effects of fluctuations in input beam current (a), input emittance (b), input beam energy (c) and intervane voltage (d) on transmission and capture according to the simulation results.

IV. TWO-DIMENSIONAL RFQ CAVITY DESIGN

The 2-D cross-section of the RFQ cavity design was done using the computer code SUPERFISH. Various geometrical parameters, describing the RFQ cross-section geometry, were optimized to attain the RF frequency of 352.2 MHz by the use of this code. This cross-section is the basic element for 3-D models.

RFQfish, one responsible program in SUPERFISH code group, assumes a four-fold symmetry, therefore sets up the geometry for only one quadrant of the RFQ cavity.

All of parameters such as average bore radius (r_0), radius of curvature of vane tip (ρ), break-out angle (α_{bk}) from tip radius to vane-blank width, half width of the blank (B_w) were determined by the beam dynamics simulation and used in SUPERFISH without any manipulation. The gap voltage (V_g), the intervane voltage used for the beam dynamics simulation, was set to 76.8 kV to normalize the electric fields. The α_{bk}, used for bit cutting of vane, was optimized as 9° and the B_w, which must always exceed the ρ, was set as 7 mm according to the beam dynamics simulation results.

The other geometrical parameters, excepting r_0, ρ, B_w, α_{bk}, were optimized by tuning vane-height (H) parameter. Each parameter was optimized by tuning H as follows: the parameter was optimized once we got the minimum power dissipation and the maximum shunt impedance. The other parameters were taken as constant during the optimization. For instance, W_s was optimized by tuning H while keeping constant of B_w, B_D, W_b, L_s, etc.

All the optimized parameters obtained from SUPERFISH are listed in Table 3. Figure 5 shows the full 2-D geometry of the RFQ electrodes constructed by CST MWS regarding to SUPERFISH results. Electric field pattern is shown in Fig. 6 in which the details around the vane tips are also shown.

Although RFQ works at quadrupole mode frequency, the frequencies of undesirable modes, such as dipole mode, can distort the quadrupole mode and cause unstabilities. Quadrupole (TE_{210}-like) and dipole (TE_{110}-like) modes were calculated by applying appropriate boundary conditions, once the parameters were optimized for one quadrant of the RFQ. The quadrupole mode frequency was determined as 352.16 MHz by applying Neumann bound-

TABLE 3. Design parameters of the RFQ

Parameters	Value
Resonant frequency (MHz)	352.16
Adjacent dipole node frequency (MHz)	341.42
Quality factor, Q	11145.3
Average bore radius, r_0 (cm)	0.317
Transverse radius of curvature, ρ (cm)	0.269
Break-out angle, α_{bk} (°)	9
Vane-blank half width, B_{w} (cm)	0.7
Vane-blank depth, B_{D} (cm)	3.6
Vane shoulder half width, W_{s} (cm)	0.705
Vane base half width, W_{b} (cm)	1.4
Vane shoulder length, L_{s} (cm)	1.712
Vane height, H (cm)	9
Vane half width, W (cm)	4.177
Corner radius, R_{c} (cm)	1.678
Vane angle 1, α_1 (°)	12.5
Vane angle 2, α_2 (°)	19.5

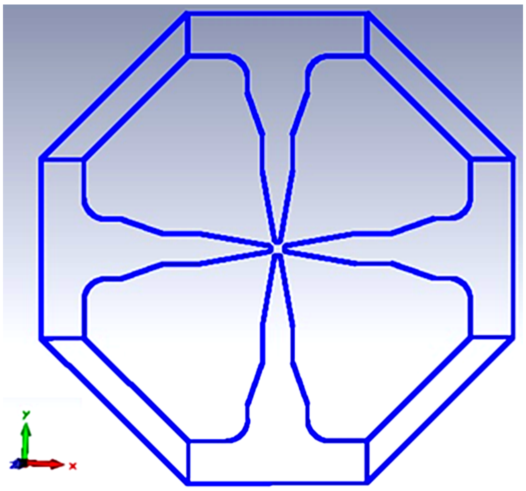

Fig. 5. (Color online) A full 2-D geometry of the RFQ electrodes constructed by CST MWS according to SUPERFISH results. The beam flows inward on z-axis.

ary condition around the vane-shoulder half width (W_{s}) in Fig. 5 and Dirichlet boundary condition around the vane-tips (Fig. 5), while the dipole mode frequency was obtained as 341.42 MHz changing the boundary condition around the vane-tips to Neumann boundary. The difference of ∼11 MHz between two modes is sufficient enough. This difference depends on the RFQ length, because the longer the RFQ is, the closer the high-order modes come to the operating mode [11]. The quality factor for quadrupole mode was calculated to be 11 145.3 using SUPERFISH.

V. THREE-DIMENSIONAL RFQ CAVITY DESIGN

Looking into more details of electromagnetic field properties in the complex structure of the RFQ cavity and benchmarking 2-D model of RFQ cavity are possible with CST Microwave Studio (MWS) because of its large mesh ratio. CST MWS also takes the advantage of Perfect Boundary Approximation (PBA) technique which delivers fast convergence in short time [12].

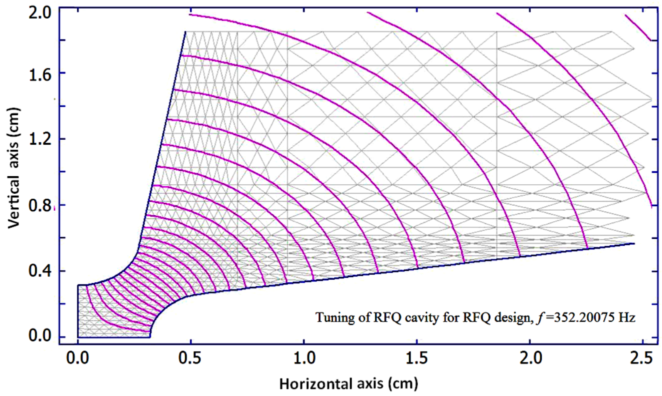

Fig. 6. (Color online) 2-D geometry of one quadrant of the RFQ electrodes obtained from SUPERFISH. The electric field pattern between the electrodes is indicated by lines.

Firstly, we have prepared the full 2-D RFQ model using the geometrical parameters obtained from SUPERFISH. Later, this 2-D model was extended to unmodulated 3-D RFQ cavity model as shown in Fig. 7.

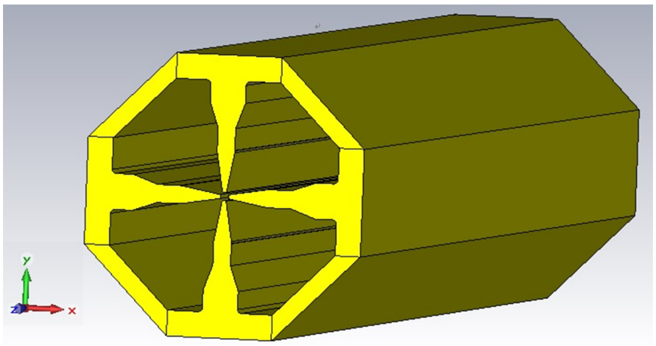

Fig. 7. (Color online) The three-dimensional unmodulated RFQ model.

The right boundary conditions should be applied to simulate the correct resonant frequency of the structure. In the x- and y- directions, the boundaries are electric ($E_t = 0$); while the boundaries are magnetic ($H_t = 0$) in the z-direction. For the quadrupole mode, the magnetic boundary conditions ($H_t = 0$) are put at the both xz- and yz-planes. But the boundary conditions at xz- and yz- planes should not be the same for the dipole mode [13]. The quadrupole mode and dipole mode frequencies obtained from CST MWS are 352.17 MHz and 345.37 MHz, respectively. These values are close to those of SUPERFISH.

VI. CONCLUSION

A beam dynamics design and electromagnetic structure analysis of 352.2 MHz and 3 MeV RFQ for TAC linear proton accelerator has been performed out of deference to beam dynamics. A 4-D uniform beam with 30 mA current and 50 keV kinetic energy has been used in simulations done by using LIDOS.RFQ software. These current and energy values have been chosen in accord with the latest feasibility studies.

Minimum emittance growth, compactness of the RFQ structure and beam transmission were figures of merit during beam dynamics simulation. Some beam dynamics parameters, such as m and Φ_s, have been tuned in the existence of space-charge effects. A transmission of ∼97% with 98.5% capture and an emittance growth of 15% have been obtained after the optimization. The optimized RFQ is 3.45 m in length without the end caps on both sides. Such an RFQ requires a total RF power of 526 kW according to the simulation results.

Error analysis has been done by introducing some variations in the input beam parameters to see how the output beam parameters are affected. Tolerance limits belonging to input beam current, input beam emittance, input beam energy and intervane voltage have been specified in this analysis.

The 2-D electromagnetic structure design of the RFQ has been done by using SUPERFISH code to prevent the distortions on quadrupole mode frequency induced by the nearest dipole mode. According to SUPERFISH results, the difference between these two modes is 11 MHz roughly. This 2-D electromagnetic design has given a high quality factor (Q) of 11 145.

The 3-D electromagnetic structure design has been done for more detailed electromagnetic structure view of the RFQ by using CST MWS software since it has a large mesh ratio. The quadrupole mode frequency and Q are 352.17 MHz and 11 677 respectively, while the dipole mode frequency is 345.37 MHz which are compatible with SUPERFISH. Based on these results, the TAC RFQ has good parameters and is less sensitive to small variations in input beam parameters. The next work belonging to the RFQ would be detailed RF analysis including thermal analysis, accelerating electric field stabilization (via cut-backs of end-vanes, and π-mode stabilizers, if it is needed [14]) which is another important and challenging step for the RFQ design.

ACKNOWLEDGEMENTS

We thank the Turkish Atomic Energy Authority (TAEK) SNRTC for benefiting from their computing facilities. Especially, we thank Alessandra Lombardi from Linac4/CERN and Saleh Sultansoy from TOBB University of Economics and Technology for their helps.

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