Beam Dynamics Design and Electromagnetic Analysis of 3 MeV RFQ for TAC Proton Linac (Postprint)

Authors: Caliskan A., Kisoglu H.F., Yilmaz M.

Date: 2023-06-18T00:00:00+00:00

Abstract

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.

Full Text

Preamble

Beam Dynamics Design and Electromagnetic Analysis of 3 MeV RFQ for TAC Proton Linac

A. Caliskan,[1] H.F. Kisoglu,[2],[3],† and M. Yilmaz[3]
[1]Department of Physics Engineering, Gumushane University, Gumushane 29100, Turkey
[2]Department of Physics, Aksaray University, Aksaray 68100, Turkey
[3]Physics Department, Gazi University, Ankara 06500, Turkey

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

Abstract: This study presents the beam dynamics design of a 352.2 MHz radio-frequency quadrupole (RFQ) for the Turkish Accelerator Center (TAC) project, which accelerates a continuous wave (CW) proton beam with 30 mA current from 50 keV to 3 MeV kinetic energy. The work includes error analysis of the RFQ, where fluctuations were introduced to input beam parameters to evaluate their impact on output beam parameters, as well as two-dimensional (2-D) and three-dimensional (3-D) electromagnetic structural design to obtain optimum cavity parameters consistent with beam dynamics requirements. Beam dynamics and error analysis were performed using LIDOS.RFQ, while electromagnetic design parameters were obtained 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

Introduction

The Turkish Accelerator Center (TAC) project [1] was approved by the Turkish State Planning Organization (DPT) in 2006. The project encompasses an infrared free electron laser (IR-FEL) & bremsstrahlung 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, developed through collaboration among more than 10 Turkish universities [2].

The envisioned proton linac will accelerate proton beams up to 2 GeV and serve as a source for effective applications in many industrial, technical, and health service areas, while also providing opportunities for research in nuclear science and high-energy physics. The primary objective is the use of this linac for energy generation based on accelerator-driven systems (ADS) technology, considering Turkey' s thorium reserves [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 [FIGURE:1]). The low-energy section, which forms the 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 to a radio-frequency quadrupole (RFQ), which is "sine qua non" for today' s heavy ion linacs [4].

This paper focuses on the beam dynamics design, error analysis, and electromagnetic structural design of the RFQ. The design specifications are given in Table 1 . We used an input beam with a current of 30 mA for the RFQ beam dynamics, consistent with the latest feasibility studies. A four-vane type RFQ was chosen for the 352.2 MHz radio frequency, and a continuous wave (CW) beam was envisaged to meet the needs of various applications, requiring careful attention to power consumption.

Beam dynamics and error analysis were simulated using LIDOS.RFQ [5]. Electromagnetic structural design parameters were obtained using SUPERFISH [6] for 2-D cavity geometry and CST Microwave Studio [7] for 3-D cavity geometry.

II. Beam Dynamics Design of the RFQ

RFQ design studies based on beam dynamics simulation were performed to optimize beam dynamics parameters in compliance with given conditions such as operating RF frequency, intervane voltage, input beam current, kinetic energy, and emittance. The beam dynamics design must achieve the desired energy and beam current at the RFQ exit while minimizing emittance growth, ensuring compactness of the RFQ, and maximizing beam transmission.

The normalized rms emittance of the input beam was chosen as 0.20 π mm mrad. The input energy should be selected as low as space-charge forces permit to achieve a more compact structure. The initial particle distribution was chosen as 4-D uniform with 10,000 particles. Some beam dynamics parameters were tuned using LIDOS.RFQ software, taking into account space-charge effects. The evolution of the modulation parameter (m), synchronous phase (Φs), minimum aperture (a), acceleration efficiency (A), kinetic energy (W), and intervane voltage (U_0) resulting from the optimization are shown in Fig. 2 [FIGURE:2].

The RFQ structure is divided into four sections in conventional design methods. The first is the "Radial Matching Section (RMS)" that adapts the CW beam to the time-varying structure of the RFQ. We reserved 7 cells, each 0.44 cm in length, for the RMS in our design. The structure consists of 316 cells with a total length of 3.45 m. As shown in Fig. 2, the minimum aperture (a) from the beam axis decreases 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, m is 1 (no modulation) and Φs is −90°, meaning there is no acceleration while focusing is maximized. Thus, the beam is not formed into bunches and the bucket has maximum length [8].

The "Shaper" section follows the RMS downstream. This section regulates the parameters as required by the "Gentle Buncher (GB)" section that follows. The 116 cells in the shaper provide slight acceleration as m rises to 1.015, with focusing still present though less than in the RMS. Φs varies from −90° to −86.7°, resulting in longitudinal shrinkage of the bucket. Acceleration efficiency (A) gently increases from 0 to 0.004 due to the small acceleration, and kinetic energy (W) increases by 0.30 keV at the end of this section, as shown in Fig. 2.

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

The final section, the "Acceleration Section (AS)," contains 83 cells where m, a, and Φs remain nearly constant. Focusing is therefore almost steady to maintain high acceleration efficiency (A) to reach the desired energy at the RFQ exit. At the end, W is 2.99 MeV, A is 0.44, m is 1.911, and Φs is −30°. The last cell of the RFQ is typically used as a "transition cell" to terminate the RFQ with quadrupolar symmetry. There is no axial potential or accelerating field in this cell, making it possible to control the orientation of the ellipse in transverse phase-space. A fringe field at the end of this cell matches the output beam with the next accelerator structure. A transition cell with a length of 33.98 mm was used in our design.

As shown in Fig. 2, the intervane voltage was chosen to be constant along the entire RFQ structure. We took the average bore radius and transverse radius of curvature of the vane tip ( ) as constant, making the capacitance of the vanes invariant and fabrication easier. This contributes to the flatness of the accelerating electric field (Ez) to prevent particle losses and simplifies error analysis. One important factor in determining intervane voltage is the Kilpatrick Criterion [9]. We chose a limitation of 1.8 times this criterion, considering the CW beam used. An intervane voltage of 76.80 kV was maintained constant along the RFQ structure. The design parameters obtained from simulation are given in Table 2 .

From Table 2, the maximum electric field is 31.62 MV/m, in accordance with the 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 the total RF power requirement of 526 kW is delivered to the beam, while 440 kW is dissipated on the structure walls (this value is 1.7 times that from SUPERFISH). The 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 RFQ exit, indicating successful bunching. Beam brightness, defined as B = I/( ) [10], is a main figure of merit. The beam brightness is 549.5 mA/(π^2 mm^2 mrad^2), as shown in Table 2. The output beam profile is shown in Fig. 3 [FIGURE:3].

III. Error Study of Beam Parameters

In the error analysis of the RFQ, we applied variations to the input beam parameters to evaluate their impact on output beam parameters. Transmission and capture efficiencies (i.e., accelerated particles) were the figures of merit in this analysis. We examined the effects of fluctuations in input beam current, input emittance, input energy, and intervane voltage on transmission and capture efficiencies using LIDOS.RFQ. The results are shown in Fig. 4 [FIGURE:4].

In the error study simulations, 95% transmission and capture were chosen as the lower acceptability limit. Based on this criterion and Fig. 4, an input beam current in the range of 10–40 mA is acceptable when other parameters remain invariant. Input beam energy from 49.5–52.2 keV is tolerable, and input emittance from 0.07 π mm mrad to 0.37 π mm mrad can be accommodated. Additionally, the RFQ operates properly if the intervane voltage is increased from 75.3 kV ($U/U_0 = 0.98$), although the operating voltage is 76.8 kV, while respecting the Kilpatrick Criterion.

IV. Two-Dimensional RFQ Cavity Design

The 2-D cross-section of the RFQ cavity was designed using the SUPERFISH computer code. Various geometrical parameters describing the RFQ cross-section geometry were optimized to achieve the RF frequency of 352.2 MHz. This cross-section forms the basic element for 3-D models.

RFQfish, a program in the SUPERFISH code group, assumes four-fold symmetry and therefore sets up the geometry for only one quadrant of the RFQ cavity. All parameters such as average bore radius (r_0), radius of curvature of vane tip ( ), break-out angle (α{bk}) *from tip radius to vane-blank width, and half width of the blank (Bw) were determined by beam dynamics simulation and used in SUPERFISH without modification. The gap voltage (Vg), which is the intervane voltage used for beam dynamics simulation, was set to 76.8 kV to normalize the electric fields. The break-out angle* α{bk}, used for bit cutting of the vane, was optimized as 9°, and the blank half-width Bw, which must always exceed , was set to 7 mm according to beam dynamics simulation results.

The remaining geometrical parameters, except r_0, , Bw, and α_{bk}, were optimized by tuning the vane-height (H) parameter. Each parameter was optimized by adjusting H to achieve minimum power dissipation and maximum shunt impedance while keeping other parameters constant. For instance, Ws was optimized by tuning H while keeping Bw, BD, Wb, Ls, etc., constant.

All optimized parameters obtained from SUPERFISH are listed in Table 3 . Figure 5 [FIGURE:5] shows the full 2-D geometry of the RFQ electrodes constructed by CST MWS based on SUPERFISH results. The electric field pattern is shown in Fig. 6 [FIGURE:6], with details around the vane tips also displayed.

Although the RFQ operates at the quadrupole mode frequency, undesirable modes such as the dipole mode can distort the quadrupole mode and cause instabilities. The quadrupole (TE210-like) and dipole (TE110-like) modes were calculated by applying appropriate boundary conditions after optimizing parameters for one quadrant of the RFQ. The quadrupole mode frequency was determined as 352.16 MHz by applying Neumann boundary condition around the vane-shoulder half width (Ws) in Fig. 5 and Dirichlet boundary condition around the vane tips, while the dipole mode frequency was obtained as 341.42

MHz by changing the boundary condition around the vane tips to Neumann. The 11 MHz difference between the two modes is sufficient. This difference depends on the RFQ length, as longer RFQs bring high-order modes closer to the operating mode [11]. The quality factor for the quadrupole mode was calculated to be 11,145.3 using SUPERFISH.

V. Three-Dimensional RFQ Cavity Design

Detailed investigation of electromagnetic field properties in the complex RFQ cavity structure and benchmarking of the 2-D RFQ cavity model are possible with CST Microwave Studio (MWS) due to its large mesh ratio. CST MWS also utilizes the Perfect Boundary Approximation (PBA) technique, which delivers fast convergence in short time [12].

We first prepared the full 2-D RFQ model using geometrical parameters obtained from SUPERFISH. This 2-D model was then extended to an unmodulated 3-D RFQ cavity model, as shown in Fig. 7 [FIGURE:7].

The correct resonant frequency of the structure requires appropriate boundary conditions. In the x- and y-directions, the boundaries are electric (Et = 0), while the boundaries are magnetic (Ht = 0) in the z-direction. For the quadrupole mode, magnetic boundary conditions (Ht = 0) are applied at both xz- and yz-planes, but these boundary conditions should differ 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, which are close to the SUPERFISH values.

VI. Conclusion

A beam dynamics design and electromagnetic structure analysis of a 352.2 MHz, 3 MeV RFQ for the TAC linear proton accelerator has been performed with careful attention to beam dynamics. A 4-D uniform beam with 30 mA current and 50 keV kinetic energy was used in simulations with LIDOS.RFQ software, with these current and energy values chosen according to the latest feasibility studies.

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

Error analysis was performed by introducing variations in input beam parameters to evaluate their impact on output beam parameters. Tolerance limits for input beam current, input beam emittance, input beam energy, and intervane voltage were specified in this analysis.

The 2-D electromagnetic structure design was completed using SUPERFISH to prevent distortions of the quadrupole mode frequency by the nearest dipole mode. According to SUPERFISH results, the difference between these two modes is roughly 11 MHz. This 2-D electromagnetic design yielded a high quality factor (Q) of 11,145.

The 3-D electromagnetic structure design was performed for a more detailed view of the RFQ electromagnetic structure using CST MWS software. 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 results. Based on these results, the TAC RFQ has good parameters and is relatively insensitive to small variations in input beam parameters.

Future work on the RFQ will include detailed RF analysis comprising thermal analysis and accelerating electric field stabilization (via cut-backs of end-vanes and π-mode stabilizers if needed [14]), which represents another important and challenging step in RFQ design.

Acknowledgements

We thank the Turkish Atomic Energy Authority (TAEK) SNRTC for providing access to their computing facilities. We especially thank Alessandra Lombardi from Linac4/CERN and Saleh Sultansoy from TOBB University of Economics and Technology for their assistance.

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Figures

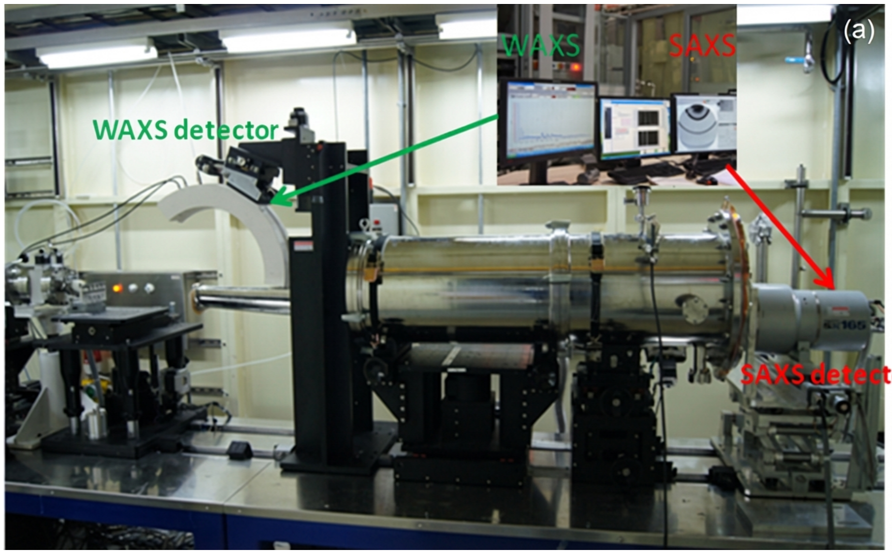

Figure 1: Figure 8

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