FULL 3D MODELING OF A RADIO-FREQUENCY QUADRUPOLE*

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Abstract

An integral part of the ongoing ATLAS efficiency and intensity upgrade is an RFQ to replace the first section of the existing injector. The proposed RFQ is 3.8 m long consisting of 106 cells with 30 keV/u input energy and 260 keV/u output energy. The RFQ was designed using the DesRFQ code which produces a file consisting of the length, modulation and the 8 coefficients of the 8-term potential for every cell. To independently check the design we created full 3D models of the RFQ including vane modulation in both Micro-Wave Studio (MWS) and Electro-Magnetic Studio (EMS). The MWS model was used for electrodynamics simulations and the EMS model was used to extract the electric fields cell by cell for beam dynamics simulations assuming the electrostatic approximation. A very good agreement was obtained between the full 3D model and the 8-term potential description in TRACK. In addition to the standard sinusoidal vane profile we studied the option of converting the cells with maximum modulation (~ 40 cells) into trapezoidal cell type. The output energy was increased from 260 keV/u to ~ 300 keV/u with minimal change in beam dynamics. This option is the final RFQ design.

ATLAS UPGRADE AND RFQ DESIGN

The efficiency and intensity upgrade of ATLAS was recently approved by DOE. The upgrade will increase the intensity of stable beams by a factor of 10 to make ATLAS the most intense low-energy stable ion beam source in the world. It will also double the efficiency for the transport and acceleration of exotic beams produced by the recently commissioned Californium Radioactive Ion Beam Upgrade (CARIBU) facility [1]. Figure 1 shows the ATLAS layout before and after the upgrade. The main new components are a Radio-Frequency Quadrupole (RFQ) and a cryomodule with state-of-the-art superconducting cavities. The RFQ will replace the very low-beta small-aperture cavities in the first PII cryomodule. The RFQ main design parameters are listed in table 1. The RFQ will consist of five identical ~ 76 cm long segments. Figure 2 shows the model for the central segment with window-type rf coupler successfully tested on the prototype 57.5 MHz RFQ [2].

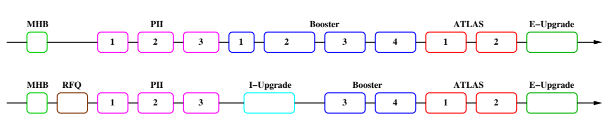

Figure 1: Layout of the existing ATLAS (top) and the proposed efficiency and intensity upgrade (bottom).

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Table 1: Main RFQ Parameters

Parameter	Value
Input Energy	30 keV/u
Output Energy	295 keV/u
Frequency	60.625 MHz
Vane Voltage	70 kV
Power	60 kW
Average Radius	7.2 mm
Length	3.81 m
Transverse RMS acceptance	2 π mm.mrad
Longitudinal RMS emittance	20 π deg.keV/u
Bunching	External 4-harmonic

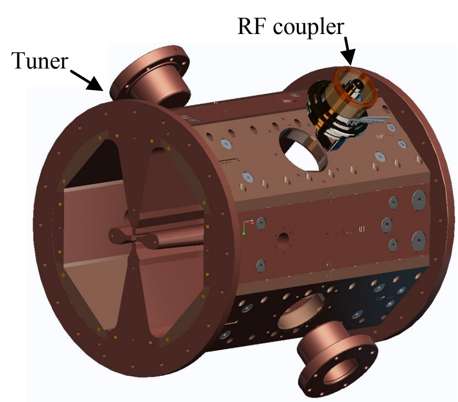

Figure 2: One of five RFQ segments.

The rest of the paper will focus mainly on the beam dynamics simulation of the RFQ.

RFQ SIMULATION: 8-TERM POTENTIAL VERSUS 3D MODEL

In order to check the 8-term potential description produced by the RFQ design code DesRFQ [3], we have developed full 3D models for the RFQ in both EM-Studio and MW-Studio [4]. The EM-studio model was used to extract the fields cell by cell to use for beam dynamics simulations in TRACK [5] assuming the electrostatic approximation while the MW-Studio model was used to independently check the field level and energy gain. Figure 3 shows a comparison of the field components along the RFQ at an aperture of one quarter the average RFQ radius ($r_0/4$). We notice a very good agreement between the 3D model and the 8-term potential description. The longitudinal component agree to better than 1 % while the transverse components agree to 1-2 %. Figure 4 shows a comparison between the two models for the synchronous particle energy and phase. We notice a maximum phase deviation of ~ 2 degrees which is a tolerable error corresponding to a maximum energy deviation of ~ 0.4 keV/u. These differences may due to the precision of the 8-term potential coefficients from DesRFQ. Figure 5 shows the dependence of the RFQ output energy on the field level factor applied to the MW-Studio field distribution calculated for a total energy of 1 Joule. In this case MW-Studio simulation results are used directly for particle tracking using Particle Studio to independently check the voltage and energy gain. From the figure we determine a threshold field level of ~ 1.18. The design field level is ~ 1.34 which corresponds to the design voltage of 70 kV in MW-Studio.

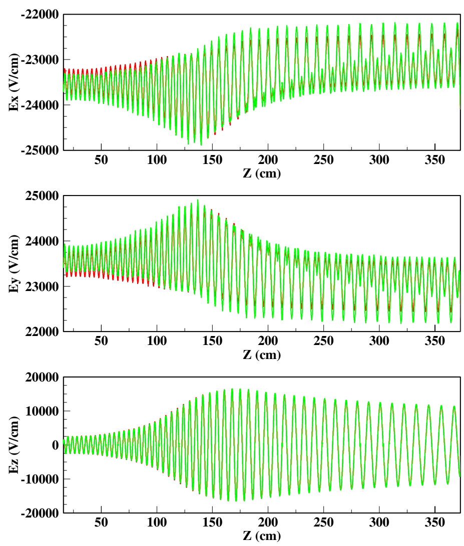

Figure 3: Comparison of the field components along the RFQ at $r_0/4$. In red is the 8-term potential description and in green is the 3D EM-Studio model.

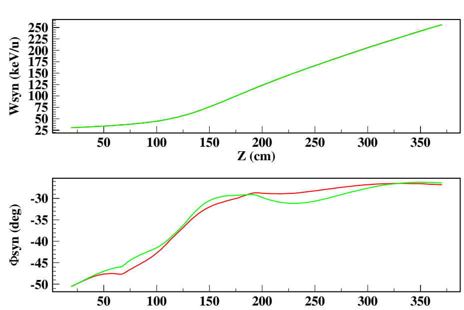

Figure 4: Comparison of the synchronous particle energy (top) and phase (bottom). In red is the 8-term potential description and in green is the 3D model.

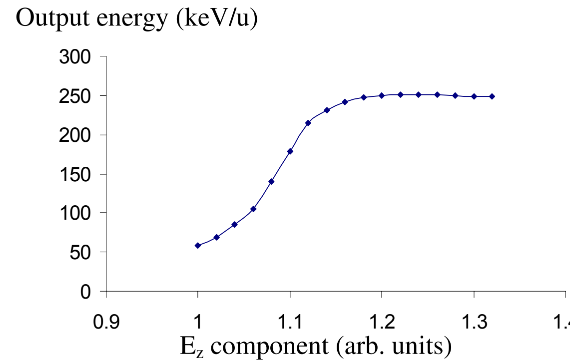

Figure 5: Output beam energy as function of the field level factor in MW-Studio.

RFQ DESIGN OPTIONS: SINUSOIDAL VS. TRAPEZOIDAL VANE MODULATION

Following the leading work of the IHEP-Protvino group [6], we have investigated an alternate design option where the last cells with maximum modulation are converted to a trapezoidal vane profile. Figure 6 shows the geometry for both the sinusoidal and trapezoidal vane profiles. The longitudinal field calculated in EM-Studio for both geometries is shown on figure 7. We clearly notice that the field profile is narrower and more peaked in the trapezoidal case which leads to a higher transit time factor and more efficient acceleration. Converting the last 40 cells from sinusoidal to trapezoidal vane modulation, the RFQ output energy increased from 260 keV/u to 295 keV/u with limited effect on the beam dynamics. Therefore our final RFQ design combines a sinusoidal vane profile in the bunching section with a trapezoidal vane profile in the acceleration section with constant modulation. Figure 8 shows the full 3D RFQ model with modulation in MW-Studio.

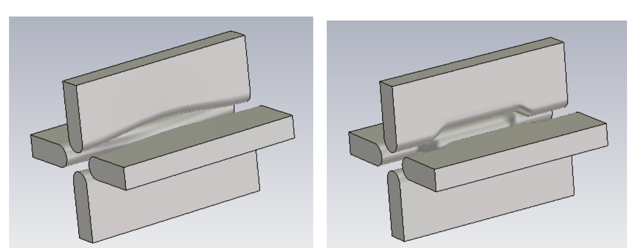

Figure 6: Geometry for one modulation period in EM-Studio for sinusoidal (left) and trapezoidal (right) vanes.

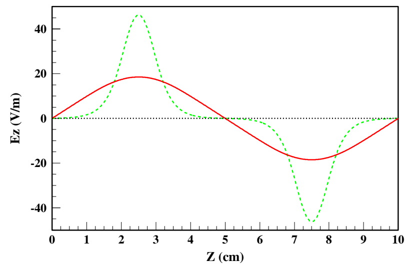

Figure 7: Comparison of the longitudinal field profile between the sinusoidal (red) and trapezoidal (green) cells.

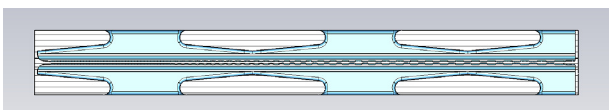

Figure 8: Full 3D model of the RFQ in MW-Studio.

NEW TYPE OF OUTPUT MATCHER

An output matcher is often used to produce an axis symmetric beam at the end of the RFQ to match the beam to a subsequent solenoid-based focusing lattice. Instead of the more standard output matcher geometry obtained by mirroring the input radial matcher, we here propose a new type of output matcher. Figure 9 shows the geometry for the new matcher. It consists of a first straight section of length L_0 at the average radius R_0 followed by a curved section of length L_c and ended with a second straight section of length L_1 at a radius R_1. Only the average radius R_0 and the total matcher length $L_0+L_c+L_1$ are defined because of the limited RFQ length. The rest of parameters L_0, L_1 and R_1 are determined by fit to produce an axis symmetric beam at the RFQ exit. A total matcher length of 1.5 times the length of a regular cell was enough to produce a symmetric beam while a standard matcher should be at least 3 times the length of a regular cell to work. This new type of output matcher relaxes the constraint on the total RFQ length because it can be much shorter. Figure 10 shows the graphics for a beam dynamics simulation of the LEBT and RFQ using TRACK for Q/A = 1/7 beam. The transverse phase space plots show the axis symmetric beam at the output of the RFQ.

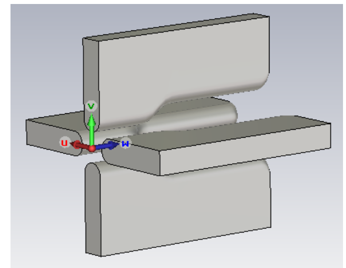

Figure 9: Geometry of the new type of output matcher.

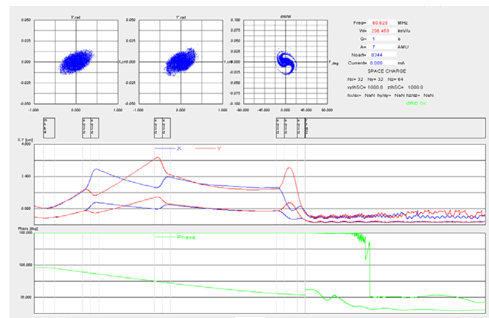

Figure 10: Beam Dynamics in the LEBT and RFQ for a Q/A = 1/7 beam. Note the axis symmetric beam at the RFQ exit.

SUMMARY

We have designed a new RFQ for the ATLAS efficiency and intensity upgrade. The original design was produced using the RFQ design code DesRFQ. To verify the 8-term potential description, we have developed a full 3D model for the RFQ. The 3D model agrees reasonably well with the 8-term potential description. In addition to the standard sinusoidal vane, we have studied a design that includes trapezoidal type cells. This option produces higher energy with limited effect on the beam dynamics. The final RFQ design combines both sinusoidal and trapezoidal vane types.

REFERENCES

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