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A graphical approach to radio frequency quadrupole design

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ABSTRACT

The design of a radio frequency quadrupole, an important section of all ion accelerators, and the calculation of its beam dynamics properties can be achieved using the existing computational tools. These programs, originally designed in 1980s, show effects of aging in their user interfaces and in their output. The authors believe there is room for improvement in both design techniques using a graphical approach and in the amount of analytical calculations before going into CPU burning finite element analysis techniques. Additionally an emphasis on the graphical method of controlling the evolution of the relevant parameters using the drag-to-change paradigm is bound to be beneficial to the designer. A computer code, named DEMIRCI, has been written in C^{++} to demonstrate these ideas. This tool has been used in the design of Turkish Atomic Energy Authority (TAEK)'s 1.5 MeV proton beamline at Saraykoy Nuclear Research and Training Center (SANAEM). DEMIRCI starts with a simple analytical model, calculates the RFQ behavior and produces 3D design files that can be fed to a milling machine. The paper discusses the experience gained during design process of SANAEM Project Prometheus (SPP) RFQ and underlines some of DEMIRCI's capabilities.

1. Introduction

The Radio Frequency Quadrupoles (RFQ) are in use at the low beta sections of all modern ion accelerators since their invention by Kapchinsky and Teplyakov in late 1970s [1]. For light ions such as H^+ and H^- operating in 300–400 MHz range, the RFQ type of choice is the, so called, "4-vane" RFQ [2]. The design of a 4-vane RFQ, which is the focus of this paper, and its manufacture require precise calculation of the relevant parameters, a good understanding of the materials and high precision machining [3]. In fact, this accelerating structure is nothing but a body (cylindrical, square or octagonal vessel) containing four carefully crafted modulated vanes, two vertical and two horizontal symmetrically distributed along the beam axis. The high precision modulation requirement on the vanes can be met by the computerized milling tools, i.e. CNC machines. However, the art of designing an efficient RFQ and the study of its beam dynamics properties necessitate repetitive lengthy calculations: An ideal task for computers. Although the two of commercially available programs [4,5], profit from years of experience in accelerator building, the main design ideas and especially the user interaction components can benefit from modern tools and concepts. Additionally, the commonly used Unix-like environment provided by Linux and OSX workstations does not have access directly to these two Microsoft Windows specific software packages.

A new project in the form of a computer code, written in C^{++}, called DEMIRCI[1] [6] is started to explore the potential of the modern concepts such as object oriented programming and ROOT environment [7]. This tool helps the designer to create an RFQ model which would achieve certain goals such as a final target energy or a fixed total accelerator length in a fully graphical environment. It calculates a large number of design and beam dynamics parameters such as energy at the end of the cavity, power dissipation and cavity quality factor for each cell. It also allows the designer to visualize a large set of parameters change along the RFQ. Another property of this tool is the interoperability with similar software in the field, either directly using the user interface or by simple exchange of plain text files.

This paper focuses on the algorithmic side of the project omitting all the installation details and instructions on how to use the actual code. These details are described elsewhere [6]. However

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[1] Meaning "blacksmith" in Turkish.

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it might be interesting for the reader to know that the project has been used successfully in multiple Unix-like environments such as OSX, Scientific Linux and Ubuntu Linux. At the writing of this note the project source code is under further development and is not open to general public, however a binary at the current state for most common platforms can be obtained by contacting the authors [8].

2. Design procedures

The classical procedure used in designing 4-vane RFQs has been around since LANL designed the first proof of principle (PoP) device. This procedure is known as the "LANL Four Section Procedure (FSP)" method [9]. According to this method, the RFQ is divided into 4 sections named as radial matching section (RMS), shaper section, gentle buncher section and acceleration section. After the steady state beam at the entrance of the RFQ is matched to time dependent electric field in the RMS, an RF bucket is formed in the shaper to prepare the beam for the gentle buncher. While the beam is being bunched, the space charge effect is also attempted to be reduced concurrently. After the beam becomes bunched, it is accelerated to the final energy at the accelerator section.

The potential between the electrodes of a single RFQ cell is given [10] by:

$$U(r,\theta,z) = \frac{V}{2}\left[\sum_{m=1}^{\infty} A_{0m}\left(\frac{r}{r_0}\right)^{2m}\cos(2m\theta) + \sum_{m=0}^{\infty}\sum_{n=1}^{\infty} A_{nm} I_{2m}(nkr)\cos(2m\theta)\cos(nkz)\right] \quad (1)$$

where r and θ are cylindrical coordinates for which z represents the beam direction, V is the amplitude of the inter-vane voltage, k is the wave parameter given by $k \equiv 2\pi/\lambda\beta$, with λ being the RF wavelength and β being the speed of the ion relative to the speed of light. Also, r_0 is mean aperture of the vanes, I_{2m} is the modified Bessel function of order 2m and the A_{nm} are the multipole coefficients whose values depend on the vane geometry.

Kapchinsky and Teplyakov argued that for practical purposes the above potential can be approximated only by the lowest order terms in the sums (hence the name "2-term potential") to calculate the EM fields around the tips of the electrodes, i.e. near the beam axis. More recently, modern tools have added few more terms to this initial approximation, in fact LANL design software uses the eight lowest order terms of Eq. (1) to characterize the EM fields in the presence of the modulated vanes. The other commercially available software, LIDOS, gives users the possibility to design RFQs in three steps; first the main parameters are defined and design optimizations are made, then accurate RF fields calculations are made with a multipole expansion of Eq. (1) and finally beam simulations are performed to understand the beam dynamics effects.

2.1. New design procedure

The parameters needed to define an RFQ can be divided into two categories: the ones which can be a function of RFQ length and the ones which are constant for a given RFQ. The resonant frequency (f), the initial ion energy (E_{in}), the input beam current (I) and the braveness factor (in terms of the Kilpatrick value) can be cited as examples to the latter. The four parameter vectors falling into the first category are: the synchronous phase (ϕ), the cell modulation (m), the minimum bore radius (a) and the inter-vane voltage (V). This last one, together with r_0/ρ where r_0 is mean aperture of the vanes and ρ is the curvature (tip radius) of the electrodes, could be kept constant along the RFQ length to simplify the design and manufacture. In case of DEMIRCI, a typical parameter's variation along the RFQ can be seen in Fig. 1. The points represented by the blue squares in Fig. 1 are the so called "reference cells" for which the values of the four key parameters are defined by the designer. In this particular example, Fig. 1 shows 20 reference cells for an RFQ of 200 cells in total. The values of the parameters at the cells in between the reference ones are obtained by interpolation assuming a simple linear function.

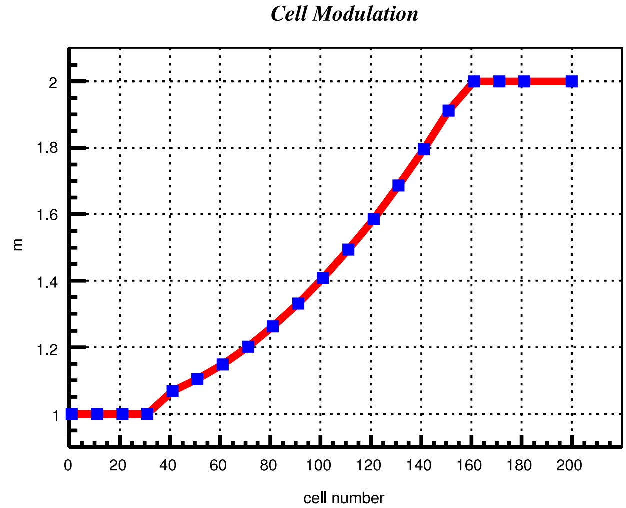

Fig. 1. Cell modulation (m) versus cell number. m is a typical RFQ parameter which changes with cell number. The meaning of blue squares and red line is explained in the text.

The number of reference cells and the total number of RFQ cells are all user defined variables. The designer might choose to define the values of the parameters for each cell, or to simply define boundary conditions for different regions of the RFQ and let the interpolation function do the rest. As a safety check, the software library ensures the monotonic increase of the reference cell numbers. Therefore a new design can be made in a pure graphical way, by simply relocating individual reference cells by using the mouse pointer e.g. to change the shape of the synchronous phase curve or by moving a complete curve, e.g. to increase the inter-vane voltage which is a constant in simple designs. This new paradigm allows quick testing of various design ideas concerning the four critical parameter vectors: ϕ, m, a and V. Although the non-graphical user interface, i.e. the command line, also exists and it could be more adequate for parameter scan studies, the graphical method has proven itself to be both more intuitive and more pedagogical for the new designers.

Once the reference curves and the other parameters are selected, the designer can simply do the interpolation and calculate all the relevant functions for each cell. The evolution of the ion beam starts with cell 0 and progresses through all cells by calculating all the variables of interest. A few simple formulas leading to the calculation of the length of the nth cell L_n, hold at voltage V_n and synchronous phase ϕ_n, the acceleration efficiency at nth cell considering 2-term potential, A_n, and the total energy (E_n) of the ions of mass m_p, charge q and speed of light c, after the nth cell, are reproduced below to give the reader an overview of the type of repetitive calculations needed to design an RFQ:

$$\begin{aligned}
\beta_n &= \sqrt{1-(m_p c^2/E_{n-1})^2} \quad (2)\\
L_n &= \beta_n\lambda/2\\
k_n &= 2\pi/(\lambda\beta_n)\\
A_n &= (m_n^2-1)/(m_n^2 I_0[k_n a_n] + I_0[k_n a_n m_n])\\
E_n &= E_{n-1} + \frac{1}{4}q\pi A_n V_n\cos(\phi_n).
\end{aligned}$$