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Novel integrated design framework for radio frequency quadrupoles

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ABSTRACT

A novel design framework for Radio Frequency Quadrupoles (RFQs), developed as part of the design of the FETS RFQ, is presented. This framework integrates several previously disparate steps in the design of RFQs, including the beam dynamics design, mechanical design, electromagnetic, thermal and mechanical modelling and beam dynamics simulations. Each stage of the design process is described in detail, including the various software options and reasons for the final software suite selected. Results are given for each of these steps, describing how each stage affects the overall design process, with an emphasis on the resulting design choices for the FETS RFQ.

1. Introduction

The Radio Frequency Quadrupole, or *F*, is the accelerating structure of choice for low energy hadron beams. First proposed by Kapchinsky and Teplyakov (K–T) in 1970 [1], the RFQ provides the most efficient method of accelerating charged hadron beams up to $\beta \approx 0.2$. This is largely a result of the RFQ providing both transverse and longitudinal focussing within a single structure, giving a large improvement in transmission efficiency over drift tube linacs as a result of the increased space charge limit [2].

One distinguishes between the two types of RFQ—the 4-vane and the 4-rod—depending on the type of electrode used. Both types use sinusoidally time-varying electric fields on four electrodes mounted close to the beam axis to produce transverse focussing: longitudinal bunching/acceleration fields are then produced by modulating the distance of the electrode tip from the beam axis. 4-vane RFQs consist of four longitudinal vanes symmetrically placed in a resonant cavity operating in the TE211 mode with end regions designed to produce a TE210-like mode in the region of the vane tips. In a 4-rod RFQ, the four rods reside inside a single larger cavity and the rods and their support structures form a series of coupled, lumped resonators. For both types of RFQ, the design process has largely followed the same path since the development of the first RFQ design codes at Los Alamos [3,4]. This involves two largely orthogonal efforts:

1. Beam dynamics design resulting in parameters describing the RFQ electrode modulations using a field approximation code that solves the K–T equations.
2. RF and mechanical design of the resonant cavity.

To first order, these two design stages *are* largely independent, as the plethora of RFQs produced using this method has proved [5,6]. Once the input beam parameters are known and the RF drive frequency is selected, the beam dynamics design does not depend on the bulk resonant properties of the cavity. While it is possible for these stages to be treated independently, at least a procedure to ensure consistency of all common parameters in both designs must be in place (the integrated design framework presented here automatically ensures this consistency).

However, the shortcomings of treating these two stages independently start to become significant at higher beam currents due to the higher electric fields required to balance the increase in space charge. This has been of particular concern for the development of the 324 MHz, 3 MeV RFQ for the Front End Test Stand at RAL [7] which must accelerate 60 mA of H^- ions at 10% duty cycle [8]. Subtleties in the shape of the field can have large effects on both the RF efficiency of the cavity and the beam dynamics. For example, the resonant properties of the cavity depend on both the bulk dimensions of the cavity *and* the proximity of the

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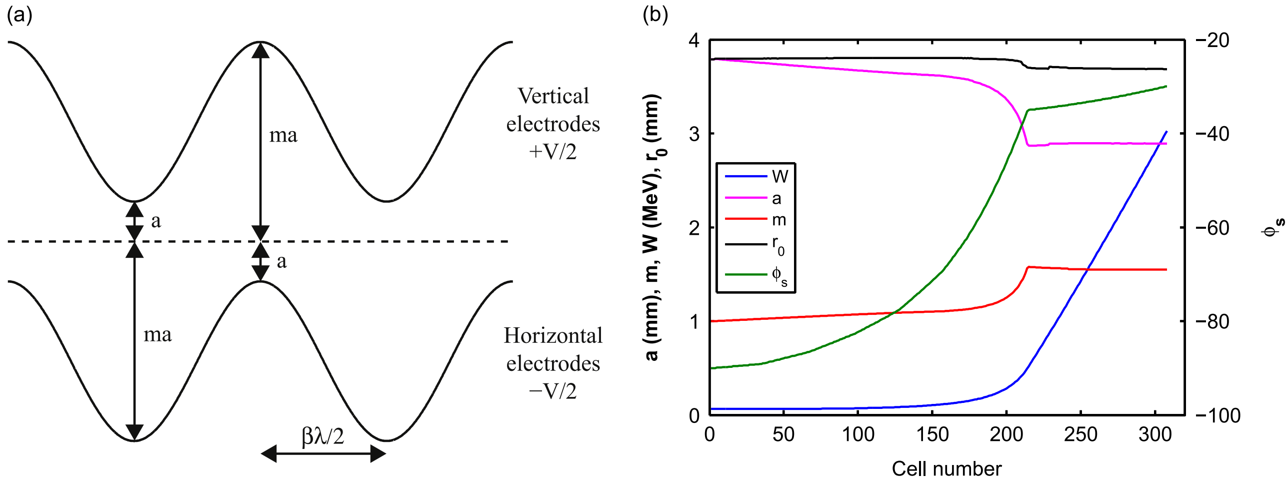

Fig. 1. Modulation parameters for an individual RFQ cell and the resulting parameters for the 4 m FETS RFQ. (a) Cell modulation parameters. (b) FETS RFQ parameters.

electrodes: for a 4-vane RFQ, the separation of the vane tips has a large effect on the capacitance of the cavity and hence the resonant frequency. Without designing the cavity as a whole, certain non-optimal limitations must be placed on the vane modulation design, such as fixing the mean electrode distance from the beam axis, r_0. Small adjustments to the modulations to improve the beam dynamics can have large effects on the capacitance: by designing the two stages independently, the effects would only be known once the cavity has already been constructed and rectifying mistakes becomes extremely costly and time consuming.

To overcome such shortcomings and provide a method of assessing the machining and alignment tolerances of the RFQ, a novel integrated design process has been developed as part of the development of the FETS RFQ. This has allowed the fusing of results from electromagnetic, thermal and mechanical modelling of the cavity with simulations of the beam dynamics based upon the electric fields close to the beam axis as a result of the subtle vane tip modulations. Using a CAD model of the cavity as the basis for all necessary simulations gives the following advantages over independent cavity and beam dynamics design:

1. All simulations are tied to a single CAD model: any modifications required as a result of adverse effects seen in one of the simulations are available to the others, including the beam dynamics simulations.
2. All simulations are carried out using the CAD model that will actually be machined. Not only does this mean that no "interpretation" is required between what appears in the simulations and how it will affect the real RFQ, but any limitations in the modelling and machining are automatically built in to the simulations.
3. All simulations are interconnected: for example, it is relatively straightforward to simulate the effect on the beam dynamics of thermal expansion of the cavity.
4. Simulating the effect of machining and alignment tolerances on the bulk electromagnetic and beam dynamics performance of the RFQ is simply a matter of introducing those "errors" into the CAD model.

In a sense, in this method the CAD model of the cavity is king: the final arbiter of what will be machined is always the CAD model. This means that improvements suggested by each of the simulation steps are governed by the limitations of the CAD modelling and machining. This prevents any changes being made to the cavity design in one of the simulations that are impossible to machine. It should be noted that 4-vane RFQs are referred to throughout, since this was the RFQ type selected for FETS [9]. However, this design framework is equally valid—and has been modelled—for the design of RFQ rods within a 4-rod RFQ, for which some additional examples are given, particularly with regard to the CAD modelling of the rods themselves.

The RFQ integrated design framework is split up into the following steps:

1. Beam dynamics design resulting in RFQ modulation parameters using a field approximation code of choice.
2. Mechanical design of the cavity geometry in a commercial CAD package.
3. CAD modelling of the RFQ modulations using the same CAD package. This step is separated from step 2 due to the complexity of the vane tip modulations but is integrated before simulations are carried out.
4. Electromagnetic simulation of the cavity to refine the resonant frequency and Q-value.
5. Thermal and mechanical stress modelling of the cavity and design of the RFQ cooling system.
6. Electrostatic field mapping of the region around the vane tips.
7. Beam dynamics simulations based on the electrostatic field map, using a particle tracking package of choice.

These steps are described in the remainder of this paper. Where possible, each of these steps has been illustrated with examples from the FETS RFQ design that required several iterations of each of these steps to reach a final design: more information can also be found in the associated references.

2. Beam dynamics design

The goal of the RFQ beam dynamics is to adiabatically bunch the incoming DC beam, then accelerate it to the final energy whilst controlling the transverse and longitudinal forces to combat space charge. The usual approach is to keep the physical size of the bunches approximately constant during bunching resulting in approximately constant charge density and hence space charge forces. To achieve this goal requires the longitudinal spatial extent of the bunches be kept constant during bunching. As the beam becomes bunched the phase length reduces but if the particles are gently accelerated at the same time the spatial length is unchanged.

As part of the design process for the ISIS 202.5 MHz, 665 keV, 4-rod H^- RFQ [10], the program RFQSIM was written [11]. Given