

CODE PACKAGE FOR RFQ DESIGNING

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INTRODUCTION

Wide experience in RFQ designing was accumulated in different accelerator laboratories throughout the world. Nevertheless new tasks on high-power, high-energy CW linac designing (for example, for ADT applications) were appeared recently. Such accelerators must be practically free of beam losses. This main condition placed more stringent requirements upon beam quality at the input of each linac part. Because RFQ is used as beginning part in above accelerators beam high-quality requirements is related to RFQ primarily. It means that existing experience in RFQ designing must be enriching by new approaches and new methodology.

New code package LIDOS.RFQ.Designer makes possible to simulate beam dynamics in RF fields of real vane shape (including gaps between RFQ section) as well as to determine channel parameters tolerances for reliable operation. The package gives users the possibility to proceed successfully from input data up to accelerating-focusing channel design and space-charge-dominated (SCD) beam simulation. Two main features are inherent in: a maximum of scientific visualization for each calculation step and the possibility to cut off undesired linac versions long before the time-consuming calculations start. The package contains codes with three levels of mathematical model complexity.

The first-level codes make only a preliminary choice of the main parameter arrays on the basis of a simplified physical model. These codes are richly supplied with visual information, that helps to find quickly the best linac version.

The second-level codes are used for channel data calculations with the real shape of the RFQ vanes. Information from the first level codes is used as input data.

The third-level codes are based on information from the first and second level codes and on complex PIC-models that are needed for a correct beam simulation in the chosen channel version.

The LIDOS.RFQ.Designer code package was presented in the report [1]. The code development is performed in two directions:

- 1) provision is made for different ion types concurrently simulation, including concurrently simulation of beams with opposite charge sign;
- 2) using of mathematical optimization methods during the channel calculation procedure.

Concurrently simulation of different ion types is topical for generation of advanced facility for the production of nuclei far from stability [2]. Optimization problems are central for generation of superpower accelerations that must be practically free of beam losses.

Codes and approaches for optimization are presented at report [3].

1. THE DISTINCTIVE FEATURES OF NEW CODE PACKAGE

The code package PARMTEQ widely used in the most accelerating centers corresponds closely with new code package both in functioning and in used mathematical methods. The recent package TOUTATIS (France) [4] belongs to the same class. This package has a possibility to take into account drift spaces between RFQ sections. The LIDOS.RFQ.Designer not only kept all features of existing packages but gives user a lot of additional possibilities.

The LIDOS.RFQ.Designer contains Advisor as the first part. Codes of this part look over of a lot linac versions and find intervane voltage, vane modulation, synchronous phase and mean channel aperture as parameters that lead to needed output beam quality.

The visualization is widely used. After operating frequency, ion charge and mass, input/output energies of ion, beam current and emittance, voltage limit are entered voltage for effective focusing and desirable beam mean radius are displayed. After selection plots of parameters listed above user can see frequencies of longitudinal and transverse oscillations as well as matched beam minimal size. Channel efficiency can be estimated and parameter plots can be changed. User observes bunching process as well as processes of acceleration and focusing. Phase portrait evolution on the background of separatrix for longitudinal motion shows points on the channel where ions leave the separatrix. Transverse motion evolution shows distance between beam boundary and aperture. Lost ion number and non-accelerated ion number are displayed also. The obtained information is enough for selection the better channel version.

Output PARMTEQ file can be entered into LIDOS.RFQ.Designer as input parameter table. It is convenient for users who have RFQ versions calculated by PARMTEQ.

Codes from Advisor are based on simple models that take into account only main components of external and beam proper fields. It is possible to use optimization methods in the frame of these models. It is possible also to choose automatically channel parameter slots if optimization criteria (for example, minimal channel length with maximal beam transmission) are selected. The main approaches for optimization are contained in [5].

2. STATISTICAL CALCULATIONS FOR TOLERANCE CHOICE

Minimization of beam losses in CW RFQ linac places more stringent requirements upon beam perturbations. Instrumental errors in vane manufacturing, installation and adjustment are sources of such perturbations. Even with very small tolerances for cell parameter deviations the potential of such perturbations is high enough for beam transmission reduction and beam quality degradation. A reason enough to such statement is provided by the fact that particle trajectories even for "ideal" (without perturbations) RFQ channel are spaced in the immediate vicinity of vane surfaces.

Due to random characters for cell parameter deviations user has only a probability for beam size to reach a given value. It means that statistical analysis can be used for the investigations. It requires repeated calculations for random realizations of channel with different cell parameter deviations.

3. POSSIBLE TYPES OF PERTURBATIONS

Random errors independently arising in each cell are the most danger. In this case there is a possibility of unfavorable realization with each next cell amplifying disturbances of all previous ones.

Let's consider possible types of random perturbations and its influence on initial beam parameters, as well as possibility of analytical and numerical investigations of different factors.

3.1. Electrode Modulation Deviation

Main effect – changes in accelerating field amplitude. It leads to coherent longitudinal oscillations and longitudinal repulsion.

Result – longitudinal phase volume increase at the output of accelerator.

Weak effect – changes in focusing field and transverse effective emittance increase produced by these changes.

Investigation method – statistical simulation.

3.2. Aperture Radius Deviation

Main effect – changes in focusing field gradient, deviation of accelerator axis from ideal line (axis may be presented as polygonal line), quadruple symmetry violation.

Result – transverse beam mismatching, coherent beam oscillations around real accelerator axis and transverse phase volume growth.

Weak effect – appearance of new random nonlinear field harmonics, changes in accelerating field.

Method of investigation – analytical estimations and statistical simulation.

Analytical theory for transverse size statistic estimation as well as for emittance growth by the action of random perturbations was generated early [5,6]. The same methods regarding to RFQ channel are given below.

3.3. Random Deviation of Focusing Field Gradient.

Let us consider that errors of focusing field gradient are caused by random deviations of cell aperture radius. In this case probability distribution function has a form

$$P(\Theta_T) = 1 - \exp(-(\ln \Theta_T)^2 / (2N\Delta^2))$$

Where $P(\Theta_T)$ is a probability of effective emittance growth no more then Θ_T times.

It follows, that the effective emittance growth coefficient will not be exceed the a limit with the probability p , if tolerances are defined by the equation

$$N\Delta^2 = -\frac{(\ln a)^2}{2 \ln(1-p)}$$

The next relation can be used for practical estimates

$$\Delta = \frac{eU\lambda}{8W_0\gamma E} \frac{x_{\max}^2 + x_{\min}^2}{2R_0^2} \delta$$

where W_0 is ion rest energy, E is beam emittance, x_{\max} and x_{\min} are maximal and minimal values of matched beam envelope, U is intervane voltage, λ is wave length of RF field, δ is unitless error for focusing field gradient.

For example, linac with operating frequency 352 MHz, voltage 100 kV, emittance 0.15 π -cm-mrad and mean aperture filling 0.7 has

$$3.8 N \Delta^2 = -\frac{(\ln a)^2}{2 \ln(1-p)}$$

If channel contains 500 cells, $p=0.95$ and $a=1.2$ then needed tolerance is $\delta=0.4\%$. If $a=1.1$ then it is 0.28%.

3.4. Displacement of the Focusing Channel Axis.

Random displacements of focusing elements with σ as rms value give rise to rms-displacement Δ of the beam center described by the relation

$$\Delta^2 = G^2 N \sigma^2,$$

where

$$G = \frac{eU\lambda}{2W_0\gamma E} \frac{x_{\max} + x_{\min}}{2R_0^2}$$

In this case, the transverse motion amplitude is a random value distributed by the following law

$$F(x) = 1 - \exp(-x^2 / \Delta^2)$$

If we want that transverse deviations of beam center with probability 0.95 not exceed 0.5 mm the tolerance will be equal 0.013 mm.

The estimates obtained at 3.3 and 3.4 show that random perturbations in RFQ channel can lead to significant beam size growth and beam losses.

The Monte-Carlo simulations were performed with the aim to estimate how possible deviations of accelerating and focusing fields can be differed the output beam parameters. The code tools described above were used for RFQ designing in favor of IPHI Project (CEA, France) Change in averaged radius position for each cell was considered as perturbation factor. It was assumed that averaged radius inside cell varies linearly. The random value distributed uniformly inside $[-\delta r, \delta r]$ was added to top value of cell averaged radius. Random values for different cells were chosen independently. Beam simulations were performed for $\delta r = 10 \mu\text{m}$ and $\delta r = 25 \mu\text{m}$. The code package described above was made statistical data processing. Beam energy losses, phase width, momentum spread, transverse size, beam center displacement, beam rms and total emittances were calculated as integral characteristics.

Accelerator parameters and detailed results of beam simulation are contained in [6-8]. They reinforce analytical estimations and give a possibility to conclude that $25 \mu\text{m}$ as tolerance is too large and $10 \mu\text{m}$ is rational for good output beam quality.

4. DIFFERENT ION TYPE SIMULATION

Provision is made for beam simulation codes by PIC methods (the third code level) to preset input beam parameters for different ion types (ion mass and charge, ion current, macro-particle number and so on). As a result user has cartoon that demonstrates beam parameter variation during acceleration process as well as beam output characteristics for each ion types.

Using code package it is possible to consider both acceleration of closely related heavy ions or ions with opposite charge signs. In the last case cartoon can be demonstrated that two bunches with opposite charge signs are shaped inside one accelerating period.

CONCLUSION

Code package LIDOS.RFQ.Designer gives a possibility to calculate RFQ parameters and make widespread investigation of multi-ion beam. It is possible to use the package for study and training.

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