INVESTIGATION ON BEAM DYNAMICS DESIGN OF HIGH-INTENSITY RFQS

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Abstract

Recently various potential uses of high-intensity beams bring new opportunities as well as challenges to RFQ accelerator research because of the new problems arising from the strong space-charge effects. Unconventional concepts of beam dynamics design, which surround the choice of basic parameters and the optimization of main dynamics parameters' variation along the machine, are illustrated by the designing Peking University (PKU) Deuteron RFQ. An efficient tool of LANL RFQ Design Codes for beam dynamics simulation and analysis, RFQBAT, is introduced. Some quality criterions are also presented for evaluating design results.

INTRODUCTION

Started by Kapchinsky and Teplyakov in 1970, the Radio Frequency Quadrupole (RFQ) accelerator has been developed as a kind of standard linear accelerator structure for low energy particles. No matter as injectors of large accelerators or independent facilities, a general tendency in the RFQ research field is to work for high-intensity beams.

Because neutrons have widely important applications e.g. clean nuclear power production, non-destructive detection and cancer treatment, the interest of using high-intensity proton or deuteron accelerators to produce neutrons as secondary particles is increasing in the world. As an essential component of such accelerator-based neutron source projects e.g. SNS, China ADS and IFMIF, the RFQ is expected to greatly improve its performance to satisfy some new severe requirements. For example, very low beam loss is a basic demand to limit the possible induced radioactivity to an acceptable level.

A 50 mA, 2.0 MeV RFQ is proposed for neutron radiography at PKU. In the case of high-intensity beams, two obvious negative influences from strong space-charge effects are defocusing and emittance growth. Therefore, some special considerations and optimization methods are required in the design work.

RFQ beam dynamics design is actually a process of choice and optimization for a multi-parameter system. All parameters could be roughly divided into two groups: (a) basic ones giving the boundary conditions of the design, e.g. frequency; (b) three relatively independent functions namely *a(z)*, *m(z)* and $\varphi_s(z)$.

CHOICE OF BASIC PARAMETERS

Basic parameters are mainly decided by four kinds of factors: (a) motivations of projects, (b) available resources like funding, equipments and applicable technologies, (c) analysis from the physical standpoint, (d) practical feasibility. In practice, a basic parameter could not be determined independently. A general case is that basic parameters are chosen as the tradeoffs of several or all kinds of factors.

Usually frequency is the first parameter to be chosen. Singly from the beam dynamics, high-intensity RFQs should use lower frequency for stronger focusing strength, which benefits to capture and accelerate higher current beams (Formula (1)).

$$B = \left(\frac{q \cdot V}{m_0 \cdot f^2 \cdot a^2}\right) \cdot \left(\frac{I_0(ka) + I_0(mka)}{m^2 \cdot I_0(ka) + I_0(mka)}\right) \quad (1)$$

where a=aperture, f= RF frequency, I_0=first order Bessel function, k=wave number, m=electrode modulation, m_0=rest mass, q=charge, V=inter-electrode voltage.

However, lower frequency will significantly increase the cavity dimensions consequently the costs, and higher one could lower the charge per bunch, which is advantageous to avoid undesired resonances and emittance growth in high-intensity RFQs.

For enough neutron production, the ^{9}Be(d, n) reaction using a 50 mA, 2.0 MeV deuteron beam is chosen for the PKU RFQ. Numerical studies show that ~200MHz frequency is suitable for high current deuteron RFQs with adequate focusing strength and aperture size. The available RF power source at ~200 MHz, the THALES tetrode TH781 [1], is adopted for the PKU D^+ RFQ. Consequently, the frequency, the duty factor and the total peak power are fixed at 201.5 MHz, 10% and 400 kW respectively.

Inter-electrode voltage mainly governs the transverse focusing strength (Formula (1)), the current limits and the acceleration efficiency. An integrated consideration of favorable transmission and structure length, ease of machining, low power consumption and the Kilpatrick Law is done for the PKU RFQ. The 80 kV of voltage i.e. 1.8E_k, which is a reasonable max. surface field proved by the practice of the LEDA RFQ, is finally adopted.

The 50 keV of input energy W_i is a compromising choice of emittance concerns. Lower W_i goes against the

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transverse emittance at the entrance to RFQ where space-charge effects are remarkable. Furthermore, as there are few acceleration in the shaper and gentle buncher sections which need be long enough for preparing a beam well in transverse and longitudinal directions, lower W_i normally leads to a shorter structure due to cell length=βλ/2.

Basic parameters of the PKU RFQ are listed as below.

Table 1: Basic parameters of the PKU RFQ

Frequency [MHz]	201.5
Input/Output energy [MeV]	0.05 - 2.00
Peak beam current [mA]	50
Inter-electrode voltage [kV]	80
Duty Factor [%]	10

BEAM DYNAMICS OPTIMIZATION

The LANL Four-Section Procedure, which conceptually divides an RFQ into Radial Matching section (RM), Shaper (SH), Gentle Buncher (GB) and Acceleration section (ACC), has been the standard solution for RFQ beam dynamics designs.

Regarding the transition point between the GB section and the ACC section as a borderline, these four sections could be simply distinguished into two phases: preparing period and accelerating period. The RM section serves to get high transverse capture at the entrance to the RFQ, the SH and GB sections aim to longitudinally change the beam from continuous to well bunched. The real acceleration is achieved by the ACC section.

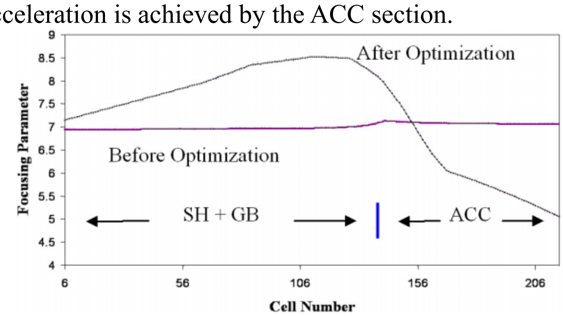

Figure 1: Variation of B before and after optimization.

Obviously, before the ACC section, the space-charge forces of intense beams are increasing with decreasing beam bunch size at low velocities and behave most significantly at the end of the GB section. Then they will be reduced because of the maximum acceleration rate.

For a typical four-section design, the focusing parameter B is held constant after the RM section in order to adapt the beam to a time-independent transverse focusing system. But from the above analysis, B is not necessary to and should not be fixed due to the changing space-charge forces along the RFQ. Therefore, the method of adjusting the variation of the focusing parameter to keep a certain ratio between the focusing force and the space-charge force is employed in the optimization design of the PKU RFQ. Fig.1 shows that B has a nearly linear growth to the maximum value until the end of GB section and then decreases gradually to the exit of the RFQ. The average focusing parameters are similar before and after optimization. This method also has the merit of getting a bigger aperture at the high energy end.

In addition, numerical simulation studies show that the peaks of beam losses usually appear at the transition points between neighboring sections, where beam parameters vary steeply. Naturally, another opmization concept of smoothing parameters' variation especially at the critical point between the GB section and the ACC section is combined into the PKU RFQ design. Fig.2 shows that the two sections are smoothly merged into together, which means particles get more acceleration in the GB section and more focusing in the ACC section. It is also helpful to short the total length of the electrodes.

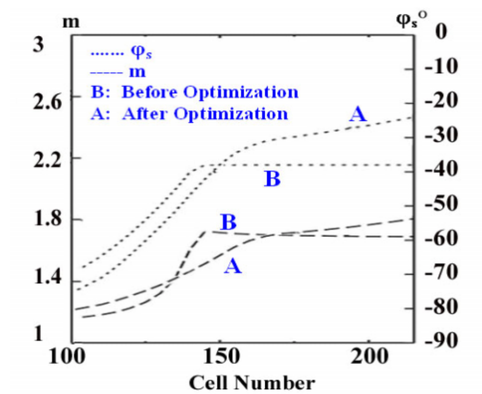

Figure 2: Smoothing optimization φs & m along the RFQ.

Table 2: Main parameters of the PKU RFQ

Parameters	Before Optimization	After Optimization
Synchronous phase [°]	-90 – -38	-90 – -25
Electrode modulation	1 – 1.73	1 – 1.79
Minimum aperture [cm]	0.26	0.28
Electrode length [m]	2.91	2.71
Cell numbers	216	216
Beam transmission [%]	91.0	98.5

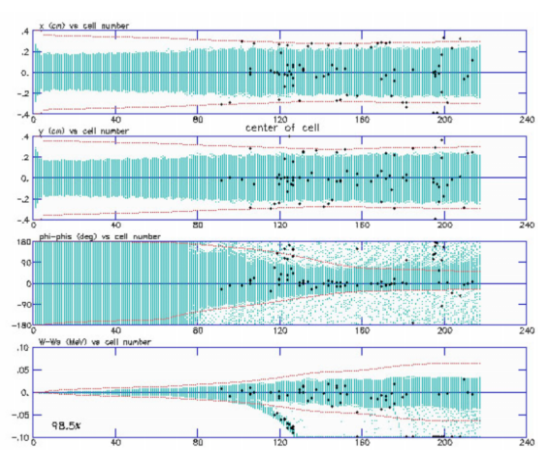

Figure 3: Beam transport simulation along the PKU RFQ.

The results based on the above two optimization methods are favourable. The beam transmission effiency increases from 91.0% to 98.5% for 5000 macroparticles. Also the RFQ is shorted to 2.71 m from 2.91 m. Fig. 3 is the beam transport plot of the optimized design.

The comparisons of main parameters and the beam losses before and after optimization are presented in the Table 2 and the reference [3] respectively.

RFQBAT COMPUTER CODE

The LANL RFQ Design Codes are the most popular beam dynamics simulation software for RFQ accelerators. A complete process of design includes the following four stages, namely calculating the current limit for a given RFQ design by CURLI, exploring the parameter space of interest and developing reference designs by RFQUICK, calculating the electrode modulation by PARI and generating the detailed RFQ design and integrating multi-particle bunches through the machine by ParmteqM [4].

To get a design scheme with very high performance, normally the optimization of beam dynamics parameters takes a lot of times, e.g. the design process of the India ADS RFQ [5]. The main disadvantages of the DOS-based LANL codes are low efficiency and poor management of input and output data. Therefore, a Windows code, RFQ Beam Analysis Tools (RFQBAT), has been developed for accelerating and extending the LANL codes since 2002.

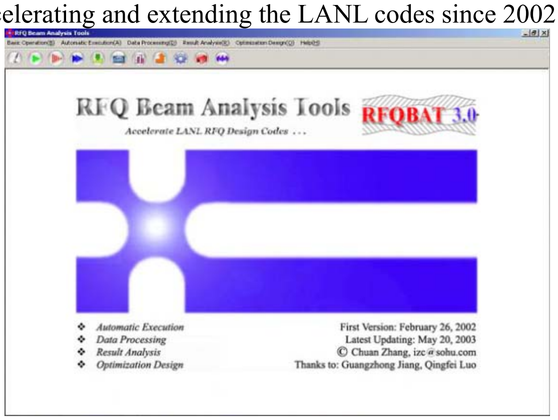

Figure 4: Start Window of the RFQBAT Code.

Though the source code of the LANL codes is not available, RFQBAT still successfully controls its running from outside with the script files saving all input data and commands. The main features of this efficient software are automatic execution, batch run, data processing, result analysis and optimization design.

It lets the running of the LANL codes need not to manually input parameters one by one any more. One automatic execution based on script files could save about 2/3 of the regular running time. After setting a certain variable and the step length, the function of batch run makes the study on the influence of an interesting parameter possible without any human workload. The RFQBAT database could not only save the input data and record all important values located in different output files for one calculation but also give the opportunity to compare and analysis relative calculations.

DESIGN QUALITY CRITERIONS

The RFQBAT Code brings the investigation on various design schemes to an easy case. Then how to evaluate the quality of a design scheme should be a critical point.

To some degree, designing RFQ accelerators is an engineering problem rather than a physical one, so the design quality criterions depend on a lot of practical factors, like the purpose of the machine, the construction costs and the ease of maintenance, etc. Here several general design quality criterions especially for high current RFQs are described.

Firstly, high beam transmission efficiency is a very important standard. Being used to produce neutrons, for example, most high current proton and deuteron RFQs require as high as possible transmission efficiency for radioactivity protection.

Secondly, a reasonable energy distribution of lost particles is very important. When some particles could not stay in the bucket of stabile oscillations around the synchronous phase at a certain moment, normally they will not be lost at once. Some of them could fly forward a distance by means of inertia without or with a little energy gain, then they hit the cavity wall and appear to be lost. Therefore, it does make sense to investigate the energy of lost particles.

Thirdly, the sensitivity of design schemes should be checked. Ion sources and input matching are not perfect, so the non-ideal beams will affect the beam transmission. A stable design scheme is important for practice [6].

In addition, the cavity size, emittance growth and aperture size should be also taken into account as functions of demands.

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