RFQ WITH AN INCREASED ENERGY GAIN

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Abstract

The radio-frequency quadrupole (RFQ) linacs are widely used in the initial part of ion accelerators. For industrial and medical applications, the size of RFQ linac as well as the construction and operation costs are important. Therefore, there is a interest to design a compact RFQ linac. In this paper, RFQ linac is studied with the aim of increasing the energy gain. Parameters of a conventional RFQ linac are usually chosen to ensure beam acceleration and stability, providing the auto-phasing and strong quadrupole focusing in the longitudinal and transverse directions simultaneously. As results, the accelerating efficiency of RFQ is limited by the transverse defocusing effect, and its value is below of a maximum value, which can be provided by RFQ electrodes. To facilitate these limitations, the well-known idea of alternating phase focusing (APF) is utilized. The APF effects boost transverse focusing, allowing to increase an accelerating efficiency, electrode voltage and decreasing average value of the synchronous phase. In this report, the examples of several carbon RFQ linacs designed according to a conventional and our modified approaches are presented, compared and discussed.

INTRODUCTION

Nowadays, there are several projects of ion accelerators for industrial and medical applications, e.g., accelerator facilities for the radiation therapy with carbon ions [1]. These accelerators employ the ion linacs as an initial part. The size and cost of these ion linacs are important and should be minimized.

The conventional ion linac consists of RFQ and drift-tube linac (DTL). RFQ linac focus, bunch and accelerate ion beam directly from an ion source. However, a conventional RFQ has a low acceleration rate in comparison with the following DTL. Therefore, the output energy of RFQ is usually limited by minimal injection energy into DTL. For example, the HIMAC linac [2] consists of 0.8 MeV/u 7 m long RFQ and the 6 MeV/u 24 m long Alvarez tanks with magnet quadrupoles, and the average energy rate of RFQ is twice lower than one of DTL.

The obvious way to reduce a total size of ion linac is to shorten the length of a conventional low-energy-gain RFQ by reducing transfer energy between RFQ and DTL. Employing DTL structure allowing the lower injection energy does it. Two linacs with low transfer energies (400 keV/u and 600 keV/u) are proposed and designed at GSI, Germany [3] and NIRS, Japan [4], respectively. These projects utilize novel DTL's with a rather long "KONUS" and APF structures, respectively. Layout of the NIRS linac with APF is shown in Fig. 1.

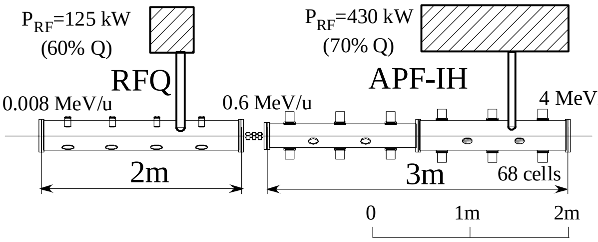

Figure 1: The injector linac layout.

However, a feasibility of these DTL linacs is not proved yet experimentally, while theoretical considerations reveal some possible troubles [3,5]. First of all, there can be practical problems with ensuring a correct voltage distributions and mechanical alignments of a large number of drift-tubes along a rather long structures at relatively severe permissible tolerances. Employing RFQ with an increased energy gain can facilitate these problems by shortening DTL structures via utilizing the higher injection energy into DTL.

RFQ WITH GRADIENT VOLTAGE DISTRIBUTION

The conventional RFQ linacs use a constant intervane voltage, V. In an RFQ, as the energy rises the cell length increases and, for a given modulation, the accelerating gradient decreases inversely with cell length.

It has been clear many years ago, that the mean accelerating gradient can be increased by using a vane average radius r_0 varying along the length proportional to ion velocity, and adjusting the tilted intervane voltage distribution at constant V/r_0 without affecting the sparking limit [6].

Several studies have proven, that required voltage tilts could be achieved in long 4-vane and 4-rod RFQ cavities within practical mechanical limitations [6,7]. Experience with 8-m long CW LEDA RFQ has proven, that the 4-vane RFQ can be correctly tuned to a complicated voltage distribution in a long cavity. These studies ensure that RF problems with a long RFQ cavities can be resolved.

Maximum energy gain in a gradient-voltage RFQ can be achieved when the voltage V and radius are exactly proportional to particle velocity, i.e. $V \propto \beta$ and $r_0 \propto \beta$. However, existing designs provide slower dependences on β, while the rate of voltage growing is slow down along the cavity and almost negligible at the RFQ exit.

The reason is that the focusing strength of a gradient-voltage RFQ is reduced by this change of voltage and

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average radius, and an effective transverse beam confinement cannot be ensured at small values of focusing strength.

GRADIENT VOLTAGE AP-RFQ

To facilitate conditions for the transverse beam confinement at higher intervane voltages, the RF defocusing effect should be reduced. The RF defocusing is proportional to the intervane voltage, accelerating efficiency, and a sine of the RF phase. Employing the lower values of synchronous phase is a way to reduce the RF defocusing. However, the stable area of longitudinal oscillations tends to shrink with reduction of synchronous phase, because RFQ operates at the auto-phasing conditions for the longitudinal oscillations.

In order to keep a large-enough area of the longitudinal oscillations at small values of synchronous phases, the phasing by a phase alternation can be utilized. This idea of phase modulation has been explored for a superconducting RFQ consisting of a set of short, independently phased resonators (RFQlets) [8]. However, proposal has not been realized due to an obvious increase in system complexity.

The transverse focusing is also boosted owing to effects of modulated phase focusing [8]. All these effects allow increasing electrode voltage and an accelerating efficiency, in RFQ. Let’s abbreviate RFQ with a phase alternating as “AP-RFQ”.

The above discussed modifications of a gradient-voltage RFQ are usually applied to Accelerator section, and other initial sections of RFQ (Radial matching, Shaper, etc.) are not changed. Therefore, these initial RFQ sections can be designed by a code applicable for a conventional RFQ, like a computer code GENRFQ [9] by Yamada, which has already been used for several low-current heavy-ion RFQs.

RFQ DESIGNS

Three 10 m long 200 MHz RFQ designs have been generated using PARMTEQ code [10]. The injection energy is of 8 keV/u and charge-to-mass ratio is 1/3. The maximum surface field is equal to 1.8 of the Kilpatrick limit. The initial sections of all designs are the same. The first design is completely generated by GENRFQ code. It is a conventional RFQ with a constant voltage. It is based on 600 keV/u RFQ designed for the NIRS project [4] and extended to the final length. The second design is a gradient-voltage RFQ with a constant synchronous phase. The third design is a gradient-voltage AP-RFQ.

For these three RFQ designs, the dependences of the ion energy and the required RF-power, P_{RFQ} as functions of the RFQ-length, L_{RFQ} have been calculated. The Figures 2 and 3 show these dependences.

For estimations of RF-power, it is assumed that the specific shunt impedance does not depend on the voltage distribution and is equal to $\rho = 70\,\mathrm{k}\Omega\cdot\mathrm{m}$. The following definition for ρ -value has been used: $\rho = \overline{V}^2 L_{\mathrm{RF}} / 2P_{\mathrm{RF}}$, where $\overline{V}$ is the value of intervane-voltage averaged over the total structure length.

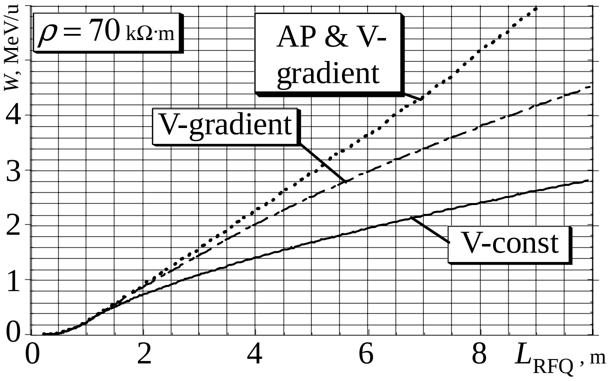

Figure 2: The ion energy versus the total length of RFQ.

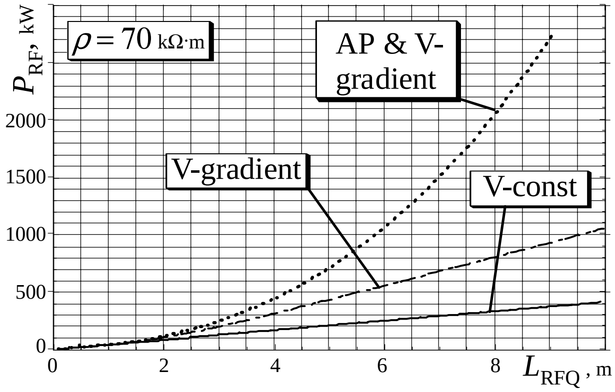

Figure 3: The RF power versus the total length of RFQ.

The beam transmission is a high enough for all tree designs. It is equal to 91%, 90%, and 81% for the 1st, 2nd and 3rd designs respectively. From the above figures, it is seen that AP-RFQ has a lowest length, and highest required RF power.

POSSIBLE LINAC LAYOUTS

There is some freedom in a parameter choice for the above shown designs. So, some optimizations may be useful and fruitful. An optimisation process done by hand has provided a better RFQ design. From this optimised design several RFQ with different energies can be derived. Their parameters are presented in Table 1.

Table 1: Examples of 200MHz ${}_{12}\mathrm{C}^{+4}$ RFQ linacs

No.	**1**	**2**	**3**	**4**	**5**	**6**
Energy, MeV/u	0.6	1.0	2.0	3.0	4.0	6.0
L_{RFQ}**, m**	1.6	2.1	3.6	5.0	6.5	9.07
P_{RFQ}**, MW**	0.07	0.12	0.30	0.59	0.95	2.07

The 0.6 MeV/u RFQ (No.1 in Table 1) is copy of the RFQ design used in the NIRS project [4]. The 6 MeV/u RFQ (No.6) can be compared with HIMAC linac: it has length about 9 m versus 31 m of HIMAC and RF power is near the same.

The 4-MeV/u 6.5 m long RFQ (No.5) can be compared with the total linac (RFQ+APF) proposed for the NIRS project [4]: it has a little bit larger length, but higher RF power (about twice). However, this “one-tank-RFQ” solution can be more reliable and easy for tuning and alignments.

The beam parameters of the 4-MeV/u RFQ are presented in Figures 4 and 5. The phase spaces of injected and output beam are shown in Figure 4. The x, energy and phase profiles of beam are shown in Figure 5.

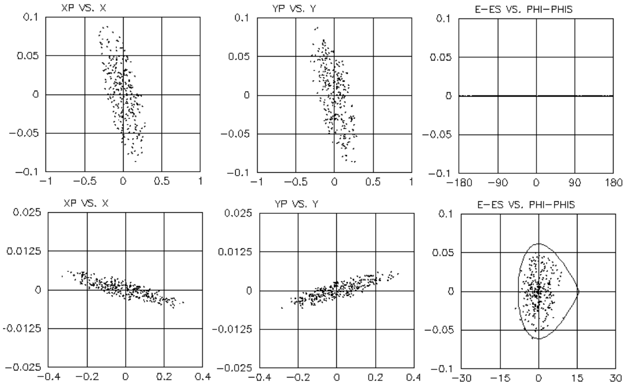

Figure 4: The phase spaces of injected (upper row) and output beam (lower row).

The figures demonstrate a good beam quality. The energy spread is about $\Delta W/W \approx \pm 0.4\%$ and exactly meets the requirements for the energy spread of output beam ($\Delta W/W \le \pm 0.4\%$).

Let’s discuss a possible modification of the linac layout adopted for the NIRS project [4]. The shortening of the 0.6-4.0 MeV/u 68-gap 3.2 m long IH-APF linac may relax levels of relatively severe permissible tolerances for this structure. One possibility is to use the 6.5 m long linac cascade consisting of the 3.0 MeV/u 5 m long RFQ (>600 kW) and a short 15-gap 1 m long IH-APF structure (~100 kW). This is a safe solution with a minimum troubles in IH-DTL.

Another possibility is to use a 6 m long linac cascade consisting of the 2.0 MeV/u 3.6 m long RFQ (>300 kW) and a 30-gap 2 m long IH-APF structure (~300 kW). The total length of the linac is about 6 m, and is longer on about 0.5 m. Instead of two different RF-generators with a total power P_{RFQ} =560 kW as for the NIRS project, two identical RF-generators can be used with a total power P_{RFQ} =600-700 kW. In spite of increasing the linac length and total RF-power, the modified layouts suggest reduced requirements for the fabrication accuracy of IH-APF linac.

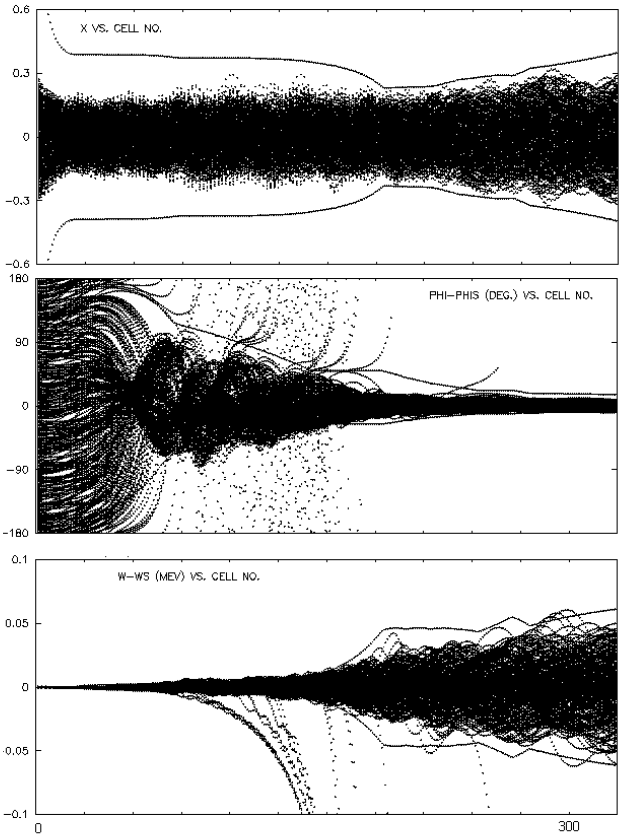

Figure 5: The x, energy and phase beam profiles versus cell number for 4MeV/u RFQ (No. 5).

REFERENCES

[1] S. Yamada, “The Progress of HIMAC…”, APAC’01, Beijing, China, 2001, p. 829.

[2] S. Yamada et al, “Injector System of HIMAC”, LINAC’90, Los Alamos, 1990, p. 593.

[3] S. Minaev, U. Ratzinger, B. Schlitt , “APF or KONUS drift tube structures … – a comparison”, PAC’99, New York, USA, 1999, p. 3555.

[4] Y. Iwata et al, “Alternating-Phase-Focused linac…”, EPAC’04, Lucerne, Switzerland, 2004.

[5] V. Kapin, Y. Iwata, S. Yamada; “Effects of Field distortions…”, report HIMAC-090‡, 2004, 43p, and this conference report.

[6] B.G. Chidley, G.E. McMichael and R.M. Hutcheon, “Tilted Field RFQ’s – an alternative design approach”, PAC 1987 by IEEE, pp.1913.

[7] L.M. Young et al, “High Power Operations of LEDA”, LINAC’2000, Monterey, p. 336.

[8] I. Ben-Zvi, A. Lombardi and P. Paul, “Design of a Superconducting RFQ resonator”, Part. Accel., Vol. 35, 1991,p. 177.

[9] S. Yamada, “Buncher Section Optimization of Heavy Ion RFQ Linacs”, LINAC’81, Santa Fe, 1981, p. 316.

[10] K.R. Crandall, R.H. Stokes, and T.P. Wangler, “RF Quadrupole Beam Dynamics Design Studies”, LINAC’79, Montauk, N.Y., p. 205.

[‡] PDF-file at site: http://weblib.cern.ch/share/hepdoc/.