DECELERATING AND ACCELERATING RFQS

A.M. Lombardi
PS Division, CERN, 1211 Geneva 23, Switzerland

Abstract

This paper presents an overview of RFQ working principles, highlights the relevant parameters and summarises the different design approaches for the high, medium and low intensity cases. Attention is then focussed on the beam dynamics design in decelerating RFQs and, in particular, on how to cope with the intrinsic problems of deceleration (e.g. physical emittance increase and reduction of the longitudinal stable area). Fields of application for decelerating RFQs and their advantages with respect to conventional decelerating techniques will also be highlighted. The beam dynamics of the RFQD, the post decelerator for the CERN Antiproton Decelerator (AD) ring, will be presented in detail. This RFQ is intended to decelerate the 5.3 MeV antiproton beam coming from the AD down to an energy of virtually zero. Several decelerating schemes have been studied to fit the experimenters' need for a high quality beam with the final energy varying in the range 0 to 100 keV. Various potential solutions will be presented and discussed, with particular attention given to the intended approach.

1 INTRODUCTION

The idea of a Radio Frequency Quadrupole Accelerator (RFQ) was born in 1970 in Russia [1,2]. Its highlights are: an alternating-gradient velocity-independent focusing and a remarkable efficiency in bunching and accelerating a continuous low energy ion beam while preserving the transverse beam quality. The efficiency of an RFQ for injection into a Drift Tube Linac can reach values as high as 90% - making it extremely attractive when compared to the 50% attainable with standard quadrupoles-and-bunchers transfer lines. It has become the key machine for attaining high-current low-emittance beams. Nowadays there are more than 100 RFQ accelerators in operation, mainly as H+,H- and heavy ion injectors but also in medical facilities, material research and material production facilities. Recently the physicist community manifested an interest [3] in using an RFQ to post-decelerate a beam coming from a ring to energies of some ten keV. This could potentially broaden the range of application of such a machine, as the theoretical deceleration efficiency is one to two orders of magnitude higher than the more widespread degrader foil technique.

2 (ACCELERATING) RFQS

The RFQ is a linear accelerator that focuses, bunches, and accelerates a continuous beam of charged particles: all three functions are performed by the electrical radio-frequency (RF) field. The RFQ consists of a cylindrical cavity resonating in the TE21 mode with four electrodes placed along the direction of propagation of the beam, which present a longitudinal modulation. The four-fold symmetry provides an alternating focussing channel, and the longitudinal modulation produces a field in the direction of propagation, which bunches and accelerates the beam. A sketch of an RFQ is reported in Fig. 1, with characteristic parameters indicated. The ratio between the focusing and the acceleration, the bunching and accelerating rates and the synchronicity between the longitudinal field and the beam are determined by the geometry of the electrodes, i.e. the aperture, the modulation and the distance between peaks and troughs on the electrode surface. Once the electrodes are machined, the RFQ is a “one-button” machine, as only the power going into the cavity can be varied. This feature, while making the RFQ easy to operate, necessitates a rigorous design phase and has given rise to the development of powerful computer codes to simulate the beam dynamics [4].

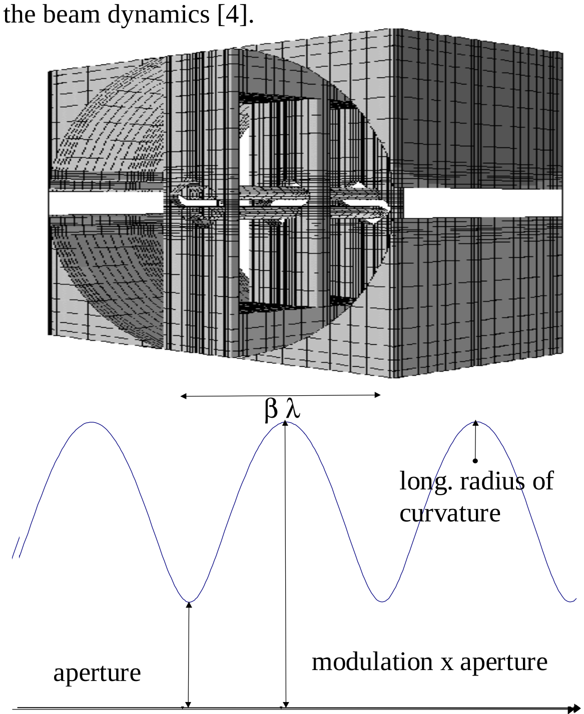

Figure 1: Sketch of an RFQ structure (top) and electrode microstructure (bottom).

2.1 Basic parameters and initial choices

For sake of completeness a list of the RFQ basic parameters [5,6,7] used throughout this paper is reported in the following.

- The focussing parameter:

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

linked to the phase advance per focussing period:

$$\sigma = \sqrt{\frac{B^2}{8\pi^2} - \frac{\pi q E_0 T \sin(\varphi)\lambda}{m_o c^2 \beta \gamma^3} - \frac{3 Z_0 q I \lambda^3 (1 - f(p))}{8\pi m_o c^2 \gamma^3 r^2 b}}$$

- The accelerating efficiency:

$$A = \frac{m^2 - 1}{m^2 I_o(ka) + I_o(mka)}$$

linked to the effective accelerating field:

$$E_0 T = AV\left(\frac{2}{\beta \cdot \lambda}\right)\frac{\pi}{4}$$

- The longitudinal radius of curvature

$$\rho_l = -\frac{A \cdot k \cdot r_o^2 \cdot I_1(mka) - 2 \cdot m \cdot a}{Ak^2 r_o^2 I_o(mka)}$$

which determines the maximum dimension of the cutting tool.

In the above: *a*=bore radius, *b*=the average beam length, β,γ=relativistic parameters, *c*=speed of light, *f*= rf frequency, *I*=beam current, *I0,1*=zero,first order Bessel function, *k*=wave number, λ=wavelength, *m*=electrode modulation, *m0*=rest mass, *f(p)*= geometrical factor, *p*=ratio of the transverse beam dimensions, *q*=charge, *r*= average transverse beam dimension, *r0*=average bore, *V*=vane voltage, *Z0*=free-space impedance (376.73 Ohm).

There are several factors that influence the choice of the basic parameters of an RFQ and each RFQ is a "special" case.

The beam-dynamics quality factors are mainly the beam output quality (transverse and longitudinal emittance, intensity), the current limit and the sensitivity to input condition, mechanical alignment and to the RF field quality (flatness, frequency stability,..). Several other "external" factor can influence the RFQ design as e.g. budget, availability of RF power and frequency of the downstream accelerator. Additionally, the structure length is always an issue, not only because of cost but also because of machining and alignment concerns.

Frequency is a fundamental design consideration as it strongly influences the focussing power and the length of the RFQ. Due to the strong frequency dependence of the focussing parameter frequencies lower than 200 MHz are more indicated for ions or very-high-current proton beams while higher frequency (300-400MHz) are more suitable for protons.

The maximum field on the vane-tip (and the maximum voltage between the electrodes) influences the acceleration rate (and consequently the length of the RFQ) and the probability of breakdown. The Kilpatrick field [8] gives a guideline: values up to 2 Kilpatrick are commonly used for low-duty-cycle machines but require a careful surface cleaning and RF conditioning.

The minimum and maximum modulation, which define the minimum and maximum acceleration rate, are determined by machining limitation. For standard machining ρ*l* should be bigger than some 5 mm.

The phase advance per focussing period is a measure of the transverse stability [5] and it should be set at a value between 20 and 40 degrees.

2.2 Design recipes

Designing an RFQ co-ordinates three aspects: the mechanic design, the RF design and electrode profile design. The field pattern in the beam region is given by the electrode micro-structure; the beam dynamics depend mainly on the electrode design, which is the only aspect this paper deals with.

An RFQ is conceptually divided into four sections [9]: the Radial Matching Section (R.M.S.), the shaper, the gentle buncher, and the accelerator. In the R.M.S. (4-6 cells) the focussing parameter is tapered up to its final value in order to adapt the beam to a time-dependent focussing system. In the shaper the longitudinal field is slowly increased in order to form the beam longitudinal structure. The shaper determines the final value of the longitudinal emittance: a smooth shaping (over several cells, up to 20-40) guarantees a small output longitudinal emittance. In the gentle buncher the synchronous phase is adiabatically changed towards a stable accelerating phase, the beam is bunched and its energy gradually increased. The end of the gentle buncher, where the modulation is maximum and the aperture minimum, defines the transverse acceptance. Finally, in the accelerator the phase, aperture, and modulation are kept constant while the beam is brought to the final energy. An exit matching section can then be added to adapt the beam to the downstream user needs. The laws of change of the defining parameters (aperture, modulation and phase) determine the transition between the different sections in the RFQ. The smoother the transition the better the output beam quality but also the longer the RFQ.

A fundamental issue when choosing an RFQ design "recipe" arises from space charge effects. These are difficult to address in the design phase as they strongly couple the longitudinal and the transverse dynamics. As a consequence it is not possible to separate bunching and acceleration because the space-charge force increase, due to bunching, must be compensated by acceleration. This imposes an extremely smooth transition both between the "shaping" and the "bunching" as well as between the "bunching" and the "acceleration". The result is that for the same beam energy increase the high-intensity RFQs turn out to be longer than the corresponding low-intensity one and that an emittance increase is unavoidable (due to bunching in the presence of space charge). During the design phase a careful trade-off between RFQ length and emittance increase has to be chosen. For low-intensity RFQs it is possible to have a fast pre-bunching section, and a boosting section (before acceleration) where the synchronous phase and modulation are varied very rapidly. Typical designs for a high and for a low intensity RFQ are shown in Fig. 2. Both these RFQs are currently operating at CERN and their nominal performances have been attained [10,11].

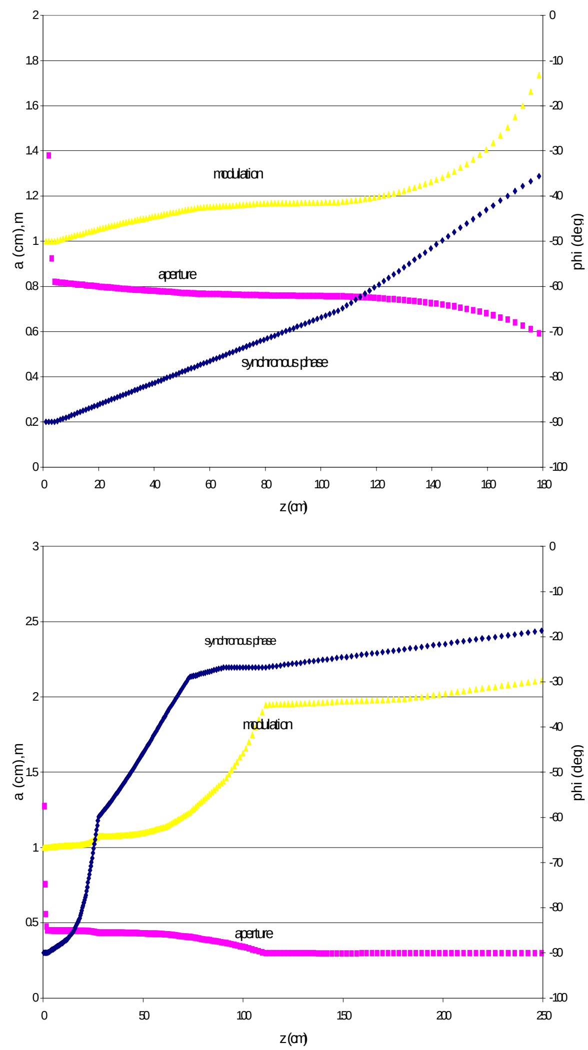

Figure 2: Evolution of modulation, aperture and synchronous phase along the axis for (top) CERN RFQ2 (200 mA protons, 90-750 keV, 200 MHz) and (bottom) for CERN LEAD ION RFQ (100 μA lead ions, 2.5-250 keV/u, 100 MHz)

3 DECELERATING RFQS

The concept of a decelerating RFQ is fundamentally different than that of a "reversed" accelerator. The main difference lies in the fact that the process of shaping and bunching the incoming beam can not just simply be done in reverse. This is not only for the inconvenience of generating an unreasonably long structure but also because of the fact that the longitudinal critical point (minimum bucket stable area) is located at the last cell of the machine. Therefore a completely different longitudinal approach needs to be applied to a decelerator RFQ.

3.1 Longitudinal dynamics and the need for a matcher

The stable motion in the longitudinal phase space in any linear accelerator can be described as an oscillation around the synchronous phase and energy along a characteristic pattern. Stable patterns lie within a separatrix [7]. In the case of an RFQ the maximum energy excursion of a particle moving along the separatrix can be expressed as:

$$\Delta W = \sqrt{2 \cdot W_s \cdot V \cdot A \cdot (\varphi_s \cdot \cos(\varphi_s) - \sin(\varphi_s))}$$

and the phase excursion (φ) follows

$$tg(\varphi_s) = \frac{\sin(\varphi) - \varphi}{1 - \cos(\varphi)}$$

where *W*s is the synchronous energy, and the rest has the same meaning as in Section 2.1

Due to the energy dependence, the stable area shrinks during the deceleration process and the separatrix of the last decelerating cell defines the acceptance of the machine. Hence the first design criterion for an RFQ decelerator is to maximise the expression above at the last cell by 1) choosing the highest vane voltage that the sparking limit allows and 2) keeping the accelerating factor (A) as high as machining limits allow. The phase should be kept as close as possible to -180°. This first criterion determines the vane voltage and the aperture and modulation of the last cell. The design of the RFQ starts then from the high-energy end: the modulation of the first cell is set to a high value (between 2 and 3) and the aperture to a value that gives the desired transverse phase advance per focussing period. From here the RFQ is generated cell-by-cell with the following procedure: with a fixed minimum acceptable longitudinal radius of curvature (ρ*l*), the maximum allowable modulation is chosen. The aperture is tentatively set to keep the focussing constant, although it can be changed to allow for a higher accelerating efficiency. With this method a rough design for the RFQ is generated. This is then refined by tuning the parameters of each individual cell to optimise locally: 1) the transverse phase advance per focussing period; 2) the maximum field on the vane-tip, and; 3) the smoothing of abrupt changes in aperture and/or modulation.

Once the design of the decelerating part is complete, the next step is to determine the longitudinal matched condition: the separatrix at the last cell is traced backwards to the input of the RFQ. This assumes that the points of the boundary rotate counter-clockwise around the synchronous phase and synchronous energy with a cell-by-cell angular velocity given by the longitudinal phase advance. The backtracked stable area defines the “decelerating acceptance”: only the particles falling in this area are successfully decelerated. It should be stressed that the decelerating acceptance is only a small fraction of the separatrix at the high-energy end and is not necessarily upright. The RFQ decelerator system therefore needs a front-end longitudinal matching section. This task can be accomplished by an adiabatic buncher system (for example a special shaping section of an RFQ) or by a discrete buncher system (conventional RF cavity). In general it is more convenient to use a discrete bunching system - the long RFQ cell length that goes with the high energy and the number of such cells typically required for smooth shaping would result in an unreasonably long machine.

The efficiency of an RFQ decelerator is determined by its front-end longitudinal matching system. The longitudinal output-beam quality depends instead on the decelerating rate at the lower energies: the faster the deceleration rate the better. This can be explained by the fact that the beam, towards the lower energies, gets closer and closer to the separatrix line and moves along an unstable path with the characteristic shape of a golf club (reversed in this case, see Fig. 3).

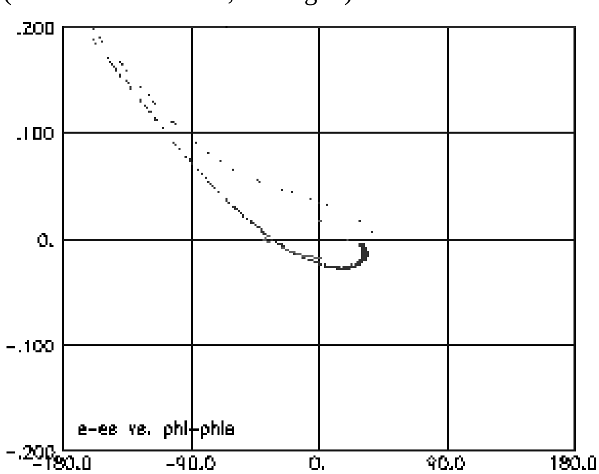

Figure 3: Characteristic path followed by particles at the boundary of the decelerating acceptance (stable particles have been removed from the plot for sake of clarity). PARMULT [4] simulation result.

3.2 Transverse dynamics

The transverse dynamics in a decelerator RFQ poses fewer problems than the longitudinal one as the process can be reversed. A standard R.M.S. can be employed at the beginning. The physical emittance increases during deceleration, and the focussing period is shortened proportionally to the beam velocity. The phase advance per focussing period (σt) is tentatively kept constant so that the beam envelope is constant along the decelerator. Conversely the divergence of the decelerated beam increases. In the critical points where σt can not be kept constant due to the more stringent longitudinal constraint, some extra cells are inserted to provide a smooth transition. This fix has been proved sufficient, in absence of space charge, for avoiding emittance increase due to mismatch.

Due to the strong beam divergence at low energy an exit matcher, to make the beam round as it exits the RFQ, facilitates the transport from the RFQ.

The RFQ is an effective focussing channel also for particles outside the longitudinal acceptance, which exit from the machine un-decelerated.

4 THE RFQD

The ASACUSA collaboration [3] is planning to use the antiproton beam coming from the CERN AD ring [12] for gas target and trap experiments. The 5.3 MeV beam coming from the ring should be post-decelerated with as-wide-as-possible energy variability around 50keV. The acceptable output energy spread is ±5 keV and the beam dimensions, a few mm.

4.1 Proposed decelerating schemes

The energy deceleration from 5.3 MeV to 50 keV is quite large: the longitudinal decelerating acceptance is 10 times smaller than the separatrix at the high energy. The possible frequencies (availability and expertise at CERN) are 200 or 100 MHz: 100 MHz makes the designing easier but would also result in an extremely long machine.

Optimisation following the criteria of Section 3 has led to the conclusion that, for a frequency of 200 MHz, the minimum energy attainable with acceptable beam quality is 50 keV. The decelerator length is about 4 meters; the equivalent structure at 100 MHz would be double this length, making it unattractive. A RF cavity performs the front-end longitudinal matching.

Some extra device must provide the energy variability, as the RFQ itself does not have this capability. Several set-ups have been considered [13], amongst which the most representative are:

- A 200 MHz RFQ decelerator to 80 keV followed by a double gap RF cavity. Energy variability: 30-130keV. The design of the double gap buncher is quite challenging due to the poor efficiency for a 200 MHz cavity at low energies.

- Use two frequencies: a high-energy section (till 400 keV) at 200 MHz, a low-energy section at 100 MHz. Energy variability: 10-140,300-500 keV. This is the best-performing solution but requires a longer drift length between the pre-buncher and the RFQ.
- The RFQ tank would be divided in two sections independently powered and phased, the second one with flat electrodes. The first part of the RFQ would decelerate the antiproton down to 100 keV, the potential drop between the wall of the second cavity and the electrodes would provide energy variability in the range 80-120 keV.
- An RFQ decelerator to 60 keV, whose inner structure, mounted on a ceramic insulator, can be raised to a DC voltage of ± 60 keV. This solution gives energy variability in the range 10-110 keV with excellent beam quality for all the output energies.

The beam quality and the cost are comparable for all the solutions; the variation in the energy range, however, is quite different. The last solution was eventually chosen based on its simplicity and the advantage of bringing the beam to an energy of virtually zero. It will be described in more detail in the next section.

4.2 The chosen solution

Particles coming from the ring at 5.3 MeV and with an energy spread of 0.2% and an overall physical emittance of 10π mm mrad are bunched by a coaxial TEM resonator loaded with double gap with an effective voltage of 47 keV. The drift (6.15 m) to the RFQ contains magnetic elements to match the beam to the RFQ transverse acceptance. The voltage and the length of the drift are optimised to maximise the number of particles in the RFQ decelerating acceptance. The RFQ, a four-rod structure, is 3.44 m long and it decelerates the beam to 63 keV. The structure holding the electrodes can be raised to a potential (± 60 keV) to further accelerate/decelerate the beam as it exits the RFQ. A corrector cavity, identical to the one at the beginning of the line, placed at the RFQ entrance, counteracts the unwanted electrostatic effect at the input. This cavity can also correct for small variations in the input beam energy.

The normalised transverse emittance is constant along the RFQ, and 46% of the incoming particles are decelerated within ± 5 keV of the nominal energy. The RFQ defining parameters are given in Fig. 4.

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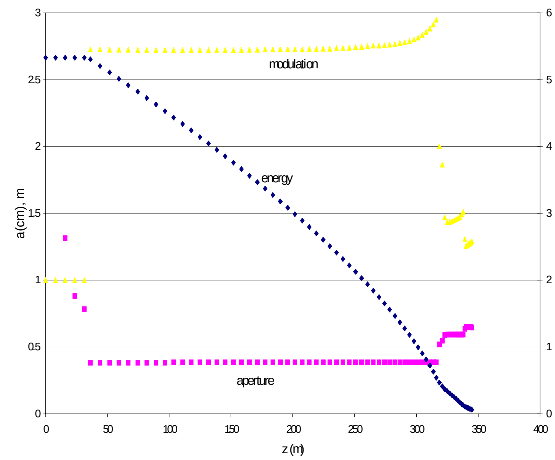

Figure 4: Modulation, aperture and synchronous energy along the decelerator RFQ

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