A REVIEW OF HIGH BEAM CURRENT RFQ ACCELERATORS AND FUNNELS*

J. David Schneider, Los Alamos National Laboratory, USA

Abstract

We review the design features of several high-current (>20-mA) and high-power (>1-mA average) proton or H^- injectors, RFQs, and funnels. We include a summary of observed performance and will mention a sampling of new designs, including the proposed incorporation of beam choppers. Different programs and organizations have chosen to build the RFQ in diverse configurations. Although the majority of RFQs are either low-current or very low duty-factor, several versions have included high-current and/or high-power designs for either protons or H^- ions. The challenges of cooling, handling high space-charge forces, and coupling with injectors and subsequent accelerators are significant. In all instances, beam tests were a valuable learning experience, because not always did these 'as-built' structures perform exactly as predicted by our earlier design codes. We summarize the key operational parameters, indicate what was achieved, and highlight what was learned in these tests. Based on this generally good performance and high promise, even more challenging designs are being considered for new applications that include even higher powers, beam funnels and choppers.

1 INTRODUCTION

Many uses [1] are identified for proposed new linear accelerators with currents of at least several tens of milliamps, and energies of approximately 1 GeV. Duty factors are often several percent for pulsed operation, or even cw (100% DF) for several applications. Radio frequency quadrupoles (RFQ) have become progressively more sophisticated since the early testing of this important concept by Kapchinskii and Teplyakov [2].

Several RFQs have been built and never completely tested, casualties of short-lived projects, combined with long and relatively expensive hardware fabrication. In other instances, times available for testing have been limited, and frequently available beam diagnostics have been less than desired. However, limited testing on a number of completed structures, combined with dramatic improvements in computers and associated design and simulation codes, has enabled the accelerator community to make significant advances in RFQ technology. Over time, the newer RFQs have become more reliable, accept higher currents, have higher transmission, display better field distributions, and demonstrate lower emittance growth. Newer structures are better cooled, of higher mechanical precision, generally of solid copper, and require less maintenance.

The challenges of building a good RFQ include:

- Optimizing the trade-off between the many design parameters.
- Maintaining adequate quality control during fabrication and assembly to ensure that the 'as-built' imperfect structure is sufficiently similar to the idealized design structure. Alternatively, we need to modify the simulation codes to model the imperfect 'as-built' structure. In several instances when this was done [3], the 'corrected' simulations very closely matched observed performance.

Additional challenges for high-power and high-duty-factor structures are ensuring proper thermal management and providing for the removal of waste heat. Dominant issues on high-power RFQs are the selection of the right materials to ensure low RF power loss, the inclusion of adequate fluid cooling channels, and the development of suitable RF and vacuum seals. Subtleties of beam design that control of beam halo and subsequent beam loss at higher energies are also very important.

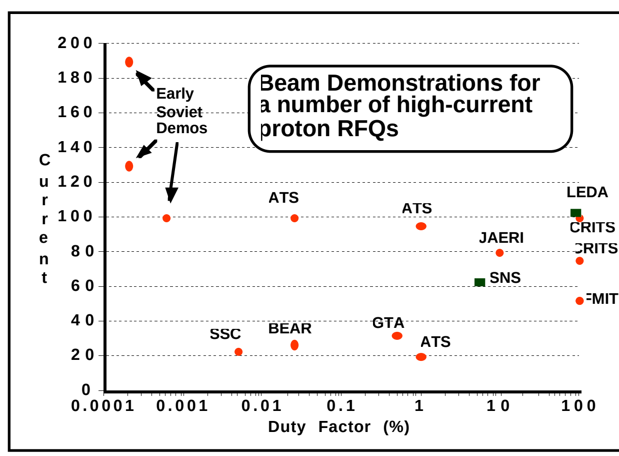

Figure 1. A depiction of some of the high-current proton RFQs that have seen beam testing. LEDA and SNS are not yet tested.

2 EVOLUTION OF RFQ DESIGNS

The earliest attempts at building RFQs met with mixed success, but provided an excellent learning experience. It was relatively easy to write equations for the basic modulated quadrupole vane tips, and use these profiles for controlling a milling machine. Effective beam simulations were constrained by slow computers and a small number of particles. Testing was compromised by mechanical errors, relatively crude alignments, difficulties in obtaining good field distributions, poorly matched input beams, choice of inappropriate materials, and our initial inattention to localized field enhancements.

Early designs often used copper-plated steel structures, striving for mechanical stability and excellent surface conductivity. Sometimes the copper plating on vane tips became pitted from repeated sparks in structures with high fields (2 Kilpatrick). An integral RF manifold was often used to distribute power. Another challenge of earlier designs was the use of 'C-seals' [4] or gold wire for good rf joints where the vanes interfaced with the outer walls. Although these demountable seals sufficed for low-duty-factor use, higher powers required a more-robust RF joint. Recent designs typically use a solid OFE copper or a copper alloy for the entire structure and employ either electroforming or brazing to completely eliminate a mechanical joint and the need for plating.

There are at least two excellent summaries of early work on RFQs. Klein [5] provided a comprehensive summary of design and operating experience by 1983. A 1985 summary paper by Schriber [6] updated the status.

But the needs for RFQs are very dynamic, particularly as new projects arise. For example, vane-coupling rings (VCRs) were very promising in the 1984 time frame because of their ability to displace the troublesome dipole modes. However, VCRs introduce scalloping into the desired quadrupole fields and require significant cooling, which is hard to provide. Recent high-duty-factor designs generally rely on other methods (such as stabilizer rods on the coupling plates and end walls) to obtain a pure quadrupole field.

During testing [7] of high-brightness systems with injectors whose emittances were greater than the RFQ acceptance, it was noted that the RFQ output beam quality was entirely independent of input beam. Only the RFQ transmission varied with input beam emittance. The RFQ was shown to be an excellent beam filter, accelerating only that beam which falls within its acceptance. In fact, the earlier difficulties of Chalk River personnel to achieve more than than 55 mA from the 1.25-MeV RFQ was due entirely to a poor match [8] from the injector.

Testing of the FMIT RFQ [9] was the western world's first attempt at cw operation. Not surprisingly, cw operation proved much more challenging that previous pulsed operation. For example, surface outgassing and the gas load from lost beam gave a real challenge to the vacuum pumps. Thermal loading, cycling, stresses, and dimensional changes appeared as serious problems. Multipacting in the outer manifold confounded high-power conditioning. This was also the first time we had to rely on only non-interceptive diagnostic devices. Subtle but important effects in the transport line prevented this massive 80-MHz RFQ from reaching full current.

Heat removal was done by water for most high-power RFQ designs, however at least two RFQs (GTA and CWDD [10,11] used cryogenic fluids. Operation at cryogenic temperatures reduced power dissipation on cavity walls by a factor of 3--5, but also reduced the coefficient of thermal expansion by nearly two orders of magnitude, resulting in a more resonantly stable structure. Super-conducting RFQ structures have been considered and partially investigated.

The GTA RFQ was machined from an aluminum alloy, then copper-plated for improved conductivity. It was designed to operate with 100% duty factor when cooled with liquid hydrogen. For safety during testing, it was operated with <1 ms pulses, and was cooled with gaseous helium at 20 Kelvin. Nominally this structure, which sat inside a larger vacuum manifold, worked fine [12]. Operational challenges included consistently providing a high-current, low-emittance H^- input beam. An initial disparity between simulations and observations was corrected only by properly including image charges and multipole effects in the simulation.

3 RECENT RFQ DESIGNS AND TESTING

Significant advances were made at CRL (Chalk River Laboratories) in developing successful CW RFQs. The RFQ1 project was begun in the early 1980's to prepare a front end for ZEBRA. By 1991, this 600-keV RFQ had successfully demonstrated its goals [13]. Then its vanes were rebuilt to increase output energy to 1.25 MeV within the same structure. The CRL program was terminated in 1993, when only about 55 mA had been accelerated by this RFQ. The unit was moved to Los Alamos, renamed the CRITS (Chalk River Injector test Stand) where, after some delays and addition of an improved injector, it accelerated up to 100 mA of protons, well above the design value of 75 mA. This successful operation of the CRITS (Chalk River Injector Test Stand) RFQ and the LEDA injector is reported in a separate paper [14] at this conference. The excellent operation of the CRITS RFQ dramatically increased our confidence in RFQ design codes and the much more ambitious LEDA RFQ.

Testing on the final CRITS RFQ emphasized the importance of having an injector with emittance lower than RFQ acceptance, and the need to have adequate beam steering and focus control of the injected beam.

The LEDA RFQ goes well beyond previous RFQ designs in terms of structure length, output energy, total dissipated power, and in beam power. Design parameters for the LEDA 8-m-long RFQ are shown in Table 1.

Figure 2. Tuning of the 8-m, 4-segment, 8-section LEDA RFQ prior to final assembly.

Table 1: Parameters of the LEDA RFQ

Operating Frequency	350.00 MHz
Accelerated Particle	proton
Input Beam	75 keV, 105 mA, 0.2 mm-mrad, rms, normalized
Output Beam	6.7 MeV, 100 mA, 0.22 mm-mrad, rms, normalized
Duty Factor	100% (cw)
Peak Surface Field	1.8 Kilpatrick, 330 kV/cm
Average Structure Power Loss	1.2 MW, 85 l/s
Total RF power	1.9 MW, fed by 12 WG irises
Surface Heat Flux	11 W/cm2 ave, 65 W/cm2 peak
Configuration (OFE copper)	4 resonant segments, 8 brazed sections, each 1 m long
Structure Tuning	static: 128 slug tuners; dynamic: water temperature

Details of beam simulations [15] and tuning [16] of this four-segment structure are described in the literature. Developments leading up to the successful implementation of tuning a multi-segment RFQ are described [17] earlier. Design and fabrication details of the LEDA RFQ are given in previous publications [18]. The assembled structure is shown in Figure 2. Cooling-water, vacuum, RF power, and instrumentation connections are being made to the LEDA RFQ at this time. This structure should be ready for first high-power conditioning in October 1998.

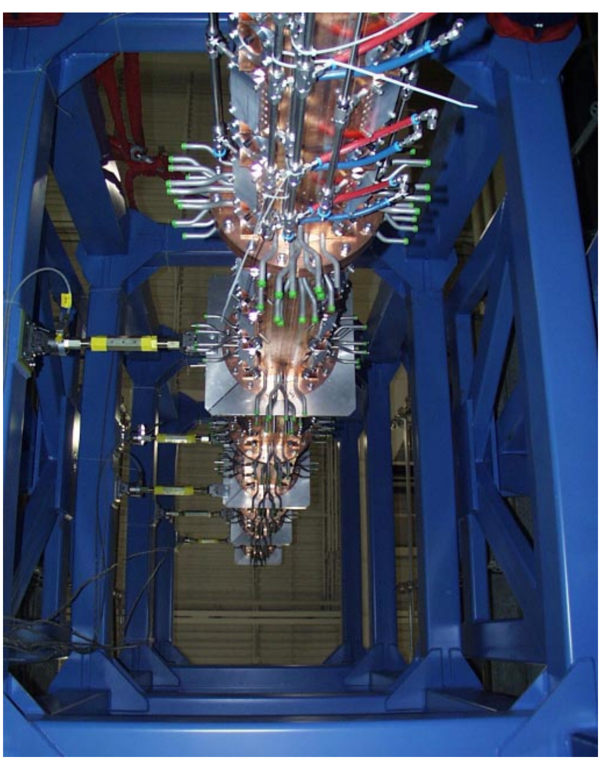

Figure 2. LEDA RFQ assembled in its support frame. A rigid support frame is used to avoid subjecting the OFE RFQ to unnecessary mechanical stresses.

3.1 RFQ Design Tools

The two primary high-power RFQ design and simulation codes are RFQTRAK and PARMTEQM. On several test cases, they gave essentially the same results, with only very small differences in α, β, and emittances. PARMTEQM uses the z position as the independent variable and assumes cylindrically symmetric space charge forces. RFQTRAK demands more computer resources, but uses a full 3-D simulation and uses time as the independent variable.

Our RFQ physicists question the detailed validity of the existing simulation codes in both the entrance and exit regions. At the entrance the beam is transitioning from a space-charge-neutralized state to unneutralized; where the RF fields are not that well known. The very last half-cell region at the RFQ exit is also poorly defined.

Recent accelerator design emphasis is shifting from maximizing the rms beam brightness to minimizing the beam lost at higher energies. We don't know precisely how much halo formation originates in the RFQ, because effects of halo, in the form of lost beam, are obvious only at much higher energies.

Early successes with conditioning low-duty-factor RFQs led to a high confidence in using high peak fields (2 times Kilpatrick). Recent operational experience with cw RFQs is pushing new designs to peak fields of less than 1.8 times Kilpatrick.

Higher peak fields generally result in an increased rate of sparkdown. But a relatively high field is valuable for other reasons, as stated below:

"*The improvements in RFQ designs from even modest increases in the allowed surface field are impressive. This is because the transverse current limit increases proportional to the square of the surface field. This results in greatly improved performance for a given RFQ structure. Alternatively it is possible to design new RFQ structures which give the same performance as at lower fields, but with much reduced length and even with less RF power consumption. An especially attractive way to trade the improved performance at high fields for a shorter RFQ is to reduce the injection energy.*" [19]

Summary of what has been learned on RFQ testing:

- Measured performance closely tracks predictions, but only if corrections are made to capture the 'as-built' errors.
- The RFQ and injector are closely matched. They must be treated as a unit. RFQ output matches predictions for only that part of the injected current that fits within the RFQ input acceptance.
- Great care is necessary during fabrication, assembly and tuning to ensure that the final structure will perform as expected, based on simulations.

4 BEAM FUNNELS

Beam funnels have been considered for many years for the purpose of approximately doubling beam brightness, i.e. to double beam current without appreciably increasing beam emittance. Multiple RFQ channels were considered as well as two lines with magnetic elements and a final RF deflector. Two funneling beam tests were performed during the US NPB (Neutral Particle Beam) program. The single-leg beam-funnel experiment [20] was very thoroughly diagnosed and confirmed that the process of transporting a single beam through all elements of a magnetic funnel added no significant emittance.

A second, undocumented NPB experiment using two beams, comprised of existing equipment, was assembled quickly and included only limited diagnostic gear and very limited beam time. However, post analysis of the experimental data confirmed that emittance growth from the combining of 25 and 30-mA beams was less than 10%.

The primary challenge for high-duty-factor funnels is to provide adequate cooling to the electrodes of the RF deflector. As with many other high-quality beam handling elements, precise alignment and tight-machining tolerances are paramount to good performance.

Challenges of a high-duty-factor funnel design:

Many transport and bunching elements may be required. Alignment and proper RF phasing requirements can be demanding. Power densities can be very high, indicating that careful attention must be given to ensuring excellent cooling. [21]

Of course, there is a lot of active work on funnel design related to heavy-ion inertial fusion drivers, where extremely high currents of high-brightness short pulses of heavy ions are needed at the target. A novel design showing two-beam RFQs and multiple-gap RF deflectors is described [22].

4.1 Beam Chopping

Linacs used for storage ring injection often have one additional requirement--to sharply and cleanly ‘chop’ the beam current to effect better injection, improved ring filling, and reduced beam losses. This complication directly impacts RFQ design, because excessive space charge argues against performing the chopping in front of the RFQ, and excessive beam stiffness is a challenge for the beam exiting the RFQ. Nath [23] et al. compare these two alternatives. Wang et al [24] propose a quadrupole slow-wave deflector for use at lower energies.

A compromise under consideration is to chop between two RFQs. As proposeded by Schempp [25] et al: “*Each RFQ line is split into two sections with the chopping line between the two RFQs to enable chopping with an unneutralised, bunched beam at a moderate energy to reduce the required chopping voltages but at an energy high enough so that the beam can be transported through the line with a minimum emittance growth*.”

These concepts and optimization remain to be tested.

5 DESIGN CHALLENGES FOR FUTURE PROJECTS

Several new projects require the use of high-energy (1 GeV) accelerators. Any beam lost at energies > 100 MeV results in structure activation and may limit options for accelerator maintenance. It is therefore extremely important to control and limit the number of particles lost at higher energies. Lost particles are predominantly those populating the beam halo. Our simulations and models indicate that much of the halo arises in the first 20-MeV of acceleration, where beam quality may be dominated by the characteristics of the RFQ. In addition to suggesting improvements in estimating and eliminating beam halo, Kolomiets, et al. [26] suggest consideration of different materials (e.g. graphite) to minimize the materials activation when there is some amount of beam loss.

5.1 Design optimization

There are still several questions about how to optimize new RFQ designs. For example, what injection energy, what peak field, at what energy to transition into the next structure? Experimental results have been mixed and thus inconclusive with respect to choice of peak fields.

Generally behavior inside the RFQ closely matches that predicted by simulation codes. However, it can be challenging for high-current injectors to provide the high-quality, high-perveance, convergent, and properly steered beam needed to ensure good RFQ transmission. Fortunately the beam exiting the RFQ is usually well-defined and consistent.

Distinguishing characteristics of most modern high-power RFQs:

- Constructed of solid copper or solid copper alloy to give best cooling, lowest RF losses, and reduced vane-tip sparking
- Use of only static (non-moving) slug tuners to avoid problems with sliding seals
- Assembly with electroforming or brazing to eliminate demountable seals
- Careful attention to machining and assembly tolerances to ensure good beam performance
- Inclusion of many cooling channels, giving high thermal conductivity, to ensure dimensional and frequency stability

Spallation-source projects requiring injection into storage rings will require development of both funnels and choppers. These will again push RFQ designs into largely unproven territory.

The very methodical approach planned for RFQ development and testing at JAERI [27] should help advance the technology base.

6 ACKNOWLEDGEMENTS

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My apologies to those RFQ programs, people, and developments I have overlooked in this review. The time pressures of leading the LEDA project have limited my work on this review.

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