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PRESENT STATUS OF RFQS*

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Summary

Since its introduction and during its recent development, the radio-frequency quadrupole (RFQ) has had a significant impact on the design, construction, and operation of ion accelerators. Characteristics of operating RFQs, those under construction and those in a preliminary design phase, will be highlighted with reference to the overall historical development. Advances in related technologies that have assisted development and establishment of the RFQ worldwide will be reviewed, including novel characteristics that could be incorporated in future devices. Predictions on where the technology is leading and what aspects require further development will be presented.

Introduction

For many years before the late 1970s, different ideas had been proposed and considered to overcome the inadequacies of transporting and accelerating ion beams to an energy suitable for injection into the most commonly employed low-beta accelerator--the drift-tube linac (DTL). These ideas included alternating phase focusing, interlaced fingers between drift-tube gaps, interdigital line components, and rectangular-bore drift tubes. The main incentives for these investigations were to improve ion-beam capture efficiency (and at the same time reduce constraints on the ion injector and transport channel), reduce injector voltage, improve rf efficiency, increase ion-beam current capability, and make the first few cells of the drift-tube linac more compatible with fabrication restrictions and with beam-current limitations. The need for an acceptable solution was becoming more critical as high-current, high-brightness, high duty-factor systems were being considered for different applications such as accelerator breeding of fissile material and heavy-ion fusion.

Most of the studies concentrated on adding effective focusing to an already existing acceleration mechanism. It was not until the opposite approach was taken (having a strong focusing system to which gentle bunching and acceleration were added) that a significant breakthrough was realized. This approach, pursued by Kapchinskii and Teplyakov[1] with their spatially homogeneous quadrupole focusing, was the beginning of what now is called the radio-frequency quadrupole (RFQ). With their breakthrough, applications (other than for high-energy accelerators) became possible for cost-effective, compact, efficient, low-voltage ion accelerators in areas that include ion-beam implanters, neutron radiography, and general-purpose sources of pulsed ion beams.

When the importance of the RFQ structure was realized in the western world after 1977, a number of projects were undertaken that led to a demonstration and detailed verification of the basic RFQ principles, an upgrading of existing facilities, and an incorporation of the RFQ into initial design studies. The RFQ has been successfully employed for accelerating H^-, H^+, H_2^+, and other heavy-ion beams to U^{2+} with good efficiency, good reliability, and overall initial acceleration simplifications. The basic principles also have been adopted by Funk[2] for the design of an interesting electron preaccelerator.

An excellent review of RFQ theory, status, and operation was published by Klein[3] in the 1983 Particle Accelerator Conference Proceedings. Because Klein gave an excellent account of the theory and a useful comparison of RFQ systems, these topics will not be covered here. This review paper will provide a brief historical introduction, a summary of research and development activities since 1983, and some comments on future possibilities. Only a few items will overlap those reported in the previous review.[3]

Historical Background

Kapchinskii and Teplyakov[1] published the theory and practical embodiment of the RFQ principle in 1970, based on work completed in the late 1960s. Not only did they describe the potential function, vane modulation, longitudinal particle energy gain, focusing efficiency, and pole surfaces, but they showed the now typical four-vane geometry and electrode cross sections. In a following paper,[4] they described how the RFQ could be utilized in ion linacs, and could simultaneously reduce injector voltage requirements and increase the beam-current limit. Kapchinskii[5] later presented details of an RFQ design for the Serpukhov injector with a discussion of allowances for errors in construction and attaining the desired electric-field configuration. In Ref. 6, Kapchinskii described the use of two RFQ structures to accelerate a deutron beam to 3 MeV before injection into a 35-MeV drift-tube linac.

Before the above RFQ developments took place, considerable work[7,8] was undertaken for application of the rf quadrupole principle to mass spectrometers. The Mathieu stability region and pole geometry were described for this particular type of transport channel (without vane modulation for bunching and acceleration) that has since been incorporated in numerous mass spectrometers.

Verification of the RFQ principle was demonstrated[9] in 1974 for proton acceleration from 100 to 620 keV using four-vane electrodes mounted in a "double-H cavity." Up to about 50% of the 400-mA input beam was captured and accelerated in a 1.4-m, 148.5-MHz structure. An RFQ injector[10] for the URAL-30 accelerator had up to 80% theoretical capture for 2-MeV output beam currents to 130 mA in a 3.5-m, 148.5-MHz structure.

The first introduction to the RFQ outside the USSR community was during informal discussions on alternating phase focusing (APF) and other focusing devices between Teplyakov, Swenson, and Schriber at the Tenth International Conference on High Energy Accelerators held at Serpukhov in July 1977. The accelerator breeder project[11] in Canada was experiencing some technical design uncertainties at that time because a 750-keV proton injector could produce no more than 30 mA cw (based on a number of cw high-voltage associated phenomena), and studies were indicating that an APF drift-tube linac (200-keV injection) had a current limit less than the required 300 mA. A possible solution, suggested in a publication[12] by Ioffe, Kapchinskii, Lazarev, and others, presented at that time was to incorporate[13] an RFQ.

Following the 1977 conference in Serpukhov, and discussions of this new concept at Los Alamos, Manca championed the first RFQ efforts[14] outside the USSR (late 1977 and early 1978). A flurry of activity began in 1978 with the initiation of beam-dynamics and rf structure studies.[15,16] By March 1978, Swenson had demonstrated almost "100% capture" with a preliminary

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beam-dynamics code. In May, Holsinger had shown how SUPERFISH could be used for calculating rf structure properties. Stokes joined the RFQ study activities in mid 1978, taking responsibility for theory efforts.

Formulation of the RFQ beam-dynamics computer code PARMTEQ (this code or a local variant is used at most Laboratories) led to theory and simulation reports[17-19] that have become the standard references. The most important beam-dynamics contributions were dividing the RFQ into sections that included the radial match and the shaper, formulation of the theory in a simple and concise manner, and a beam-dynamics treatment modeled on the highly successful PARMILA computer code. Associated with this development were later additions for adding a prebuncher section and for changing the exit of the RFQ to permit a growth in longitudinal phase space.

Work on the Los Alamos proof-of-principle RFQ began in April 1979 with the decision to rf couple to the RFQ structure by use of a manifold that consisted of the PIGMI[20] prototype DTL tank. Successful high-power operation with beam was obtained February 14, 1980. The good agreement achieved between theory and experiment was described in Ref. 21. In the five years since this achievement, a number of RFQ structures have been designed, installed, and put into operation, incorporating improvements as the technology improved. Reference 3 provides an excellent summary for much of the activity to 1983. A separate review on developments in the USSR to 1982 can be found in Ref. 22. The following sections discuss activities and highlight technology development over the past two years.

RFQ Status

The most common geometries for RFQ structures are the four-vane,[15] four-rod,[23] and split-coax.[24] The latter two geometries are most effective for rf frequencies less than about 150 MHz, whereas the former is best for frequencies greater than 150 MHz. In general, an RFQ above 1000 MHz becomes complex to design and build. Below about 50 MHz, there is an incentive to consider spiral-resonator geometry.[25] The four-rod and spiral-resonator geometries lend themselves easily to multiple beam arrays.[26]

Most four-vane RFQ structures employ loop coupling to only one of the four quadrants. The first two Laboratories discussed below have made use of a manifold concept to drive all four quadrants in an equal manner. Most RFQ structures exhibit a quality factor that is one-half the theoretical value. The loss is probably associated with a combination of end-wall losses, tuners, vacuum ports, coupling irises, material quality, and mechanical rf joints.

Saturne National Laboratory, France

The 2.3-m, 200-MHz, pulsed, four-vane structure[27] has vanes made from mild steel that were copper plated at GSI. The four quadrants are driven from a manifold that surrounds the structure. The vanes should sustain twice the Kilpatrick limit (2 Kp) but have only been operated at 1 Kp with ions having a q/A ratio of 0.5 because of a lack of rf power and no attempt to operate with q/A = 0.25. The system works without problems with about 1500 hours logged for about 50% of the normal SATURNE operation.

Peculiarities of the RFQ include no vane coupling rings (VCRs), an exit debunching section to reduce output momentum spread, an exit radial matching section to match for an output dc beam and laser welding of a flexible copper strip between the vane and cavity wall block.

First beam was obtained February 22, 1984, after several weeks of serious multipactoring problems during early conditioning. Baking of the manifold cured the multipactoring problems. Dynamics of the output beam agreed with theoretical calculations--the exact orientation of output phase ellipses were obtained. Future work will include studies of VCRs and alignment tolerances on low-power models.

Los Alamos National Laboratory

The four-vane FMIT structure is described in detail in a following paper;[28] that discussion will not be repeated here. This 80-MHz cw structure has vanes made of copper-plated mild steel and is manifold driven. Most of the problems associated with getting the structure operational with beam can be traced to multipactoring (which was solved by heating and TiN coating) and overheating caused by inadequate cooling (solved by improving the cooling and the rf mechanical joints). The structure has been accelerating cw H_2^+ beam routinely since November 1984. Two important factors for operating reliably with high-power cw beams are providing adequate cooling to all rf surface areas and employing excellent nonintercepting beam monitors.

An interesting FMIT output beam-emittance result was the rotation of one of the output phase planes relative to the simulation prediction. This difference is now under investigation and may be associated with half-cell fields between the exit end of the vanes and the smaller circular output beam aperture.

Work continues on H^- beam parameter studies using a 2-MeV pulsed four-vane RFQ structure.[29] One interesting development[30] was the employment of end-tuning stubs that are inserted between the vane ends.

Future activities include resonant-coupling schemes for stabilizing quadrant fields, loop-coupling investigations, multiple drive studies, surface breakdown studies, and improved construction techniques.

Brookhaven National Laboratory

The 1.5-m, 200-MHz, pulsed, four-vane RFQ structure[31] employs copper-plated mild steel vanes. Each quadrant is driven by two rf coupling loops for a total of eight drive connections. The structure has operated reliably from the first day of commissioning with a total of about 2000 operating hours logged.

The RFQ operates so stably and reliably at about 1.7 Kp that very little attention is paid to the accelerator. Only at turn-on is a short period necessary to permit the structure to reach equilibrium; the vanes are cooled only by conduction to the outer wall.

Future plans include construction of another RFQ to replace one of the Cockcroft-Walton injectors.

Lawrence Berkeley Laboratory

An important contribution, which has since been incorporated in most RFQ structures, was the demonstration[32] of the usefulness of VCRs in an RFQ cavity. A 2.2-m, 200-MHz, pulsed four-vane structure,[33] (that has copper-plated mild steel vanes) was built as a preinjector for the Bevatron injector. The RFQ was well engineered and was commissioned to 2 Kp without any difficulties. The structure was designed to incorporate a special prebuncher section and precision wall pickup loops for monitoring rf fields.

As part of a GSI/CERN/LBL collaboration, LBL has constructed a 0.86-m, 200-MHz, pulsed four-vane RFQ to accelerate oxygen to 139 keV/amu. In June, the structure should be shipped to GSI to be tested with an ECR source before being shipped to CERN in November for injection tests with the old Linac 1.

Future plans may include other RFQ projects including aspects of higher duty cycle.

Chalk River Nuclear Laboratories

Work continues on their 1.5-m, 270-MHz, cw, four-vane structure[34] with beam operation planned for late 1986. The solid OFHC copper vane tip will be brazed to a mild steel base using Pacusil 5, a process to be followed by copper plating. A prototype 1.5-m vane has been successfully fabricated using this brazing technique. The structure, to be operated between 1.5 and 2.0 Kp, will investigate multiple- and single-beamlet acceleration, heavy beam loadings and multiple rf drives. A novel feature of this structure is the use of a copper seal (similar to conflat gaskets) to make the vacuum and rf seal between the vane and the outer wall.

Successful operation of the 0.4-m, 270-MHz Sparker RFQ structure[35] demonstrated many aspects of RFQ design that are incorporated into the above RFQ1 structure. Aspects of light emission, x-ray emission, voltage levels (2.3 Kp cw, 3 Kp pulsed), microdischarges, and background gas were important features of the completed experimental program.

Future activities include RFQ1 revaning (simple replacement), four-rod device studies[36] and an investigation of high-current, higher-order effects.

CERN

The 1.4-m, 200-MHz, pulsed, four-vane structure[37] has been operating since March 1984 as the injector for an Alvarez linac, logging about 1500 hours of beam operation. The RFQ operates reliably with maximum fields of about 1.8 Kp. Single-loop coupling is employed for the structure without VCRs. Vanes are copper-plated mild steel, and TIG welds were used in situ for making rf contacts.

Future plans include construction of RFQ2[38] as an injector for Linac 2 with output parameters of 750 keV for more than 200 mA.

University of Frankfurt

Many activities continue on the complete range of RFQ geometries: split-coax, four-rod, spiral-resonator, multichannel-rod, MEQUALAC, and four-vane. The team of specialists was responsible for development and introduction of the interesting four-rod geometry. The rf efficiency for a four-rod structure can be similar to that of an equivalent four-vane structure if the rod supports are made wide enough,[36] as long as careful attention is paid to other compromises.

Work on beam-transport experiments has been initiated with a spiral-loaded (unmodulated vane) RFQ. Several four-rod structures[39] have been built for studies of proton and heavy-ion injectors. Work on a four-vane (four-rod as a backup) RFQ is under way for the HERA proton injector.[40] Studies on surface breakdown,[41] electrode profile,[42] and field stabilization[43] have demonstrated important consequences for possible RFQ improvements. Development of the split-coax, heavy-ion structure,[44] and the FOM-MEQUALAC structure[45] have shown many interesting developments.

Gesellschaft für Schwerionenforschung

The first split-coax module[46] has been accelerating beam since November 1983. Electrodes of Elmedur X (copper with 0.75% Cr) have been employed in the 1.5-m-long structure. This geometry is inherently rf stable and modular with good rf efficiency and mechanical stability. Beam tests with Ar^+, Kr^+, and Xe^+ have shown beam-loading effects, as indicated by rf pickups from the structure. No problems with sparking, x rays, or rf coupling have been observed. Four additional split-coax modules are being fabricated.

USSR

Activities[47] continue at IHEP and ITEP on four-vane geometries with development of vane-strapping techniques to suppress the dipole modes that would have been in proximity to the operating quadrupole mode. A 3-MeV injector at 150 MHz has been in operation at ITEP since 1982, with 97% acceptance and an output proton current of 100 mA. Work on spiral-resonator four-rod geometries is under way to investigate Bi^{2+} acceleration in a 6-m structure at 7 MHz.

KFA, Julich

Design work continues on the 3-m, 100-MHz, four-vane RFQ prototype[48] for SNQ, employing copper-plated mild steel vanes, VCRs, loop coupling, and piston tuners. A beam loading of about 40% is expected in this 100-mA proton injector.

Institute for Nuclear Study, Tokyo

The 1.2-m, 100-MHz, cw, four-vane RFQ structure LITL has operated successfully[49] with ions up to Li^+ for a total of 300 hours with beam. Work is under way on the 7-m TALL structure[49] without VCRs.

Modeling[50] has been initiated on a multimodule 2.1-m-long, 0.4-m-diam, 50-MHz split-coax RFQ with modulated vanes.

KEK National Laboratory for High-Energy Physics

A 1.4-m, 200-MHz, pulsed four-vane structure[51] to accelerate H^- to 750 keV is under construction at KEK. Reference 51 provides results on surface preparation by electropolishing and on the associated consequences from voltage-breakdown measurements.

Other Laboratories

RFQ design and modeling work is under way at other institutions and Laboratories. Two examples of this type of work follow. Fermi National Accelerator Laboratory is considering the design of a 425-MHz, 2-MeV RFQ for injection into a compact 250-MeV superconducting synchrotron. TRIUMF is considering a 23-MHz RFQ (possibly four-rod) that will be the first part of a post accelerator following ISOL (isotope separator on line) to accelerate ions to 2 MeV/amu. Plans call for a 1.5-Kp device operating cw with less than 100 kW for the 9-m structure.

Miscellaneous

Most results of surface breakdown studies show that cw systems should be functional at 2 Kp whereas pulsed systems (<1 ms) should function at 3 Kp. These studies also have indicated that solid copper does not pit or erode as badly as copper-plated surfaces.

For rf structure modeling, a number of computer codes based on distributed lumped-elements are available. The best code for versatility and agreement with measurements appears to be that described by Hutcheon.[52]

Beam-dynamics simulations are usually performed using PARMTEQ or a variant of this code. Numerous design recipes are used throughout the world to determine the first-order design parameters. Recent additions to the available computational tools include a true three-dimensional code[53,54] (with image-charge forces) and PARMTEQ improvements[55] to cover the fringe fields at the entrance and exit of an RFQ.

Future Activities

A number of interesting aspects of RFQ structures are possible in the future. Reference 56 describes possibilities of an increased modulation factor for an RFQ and cw aspects of a superconducting four-rod geometry. Much higher output energies might be possible from such a device.

In Ref. 57, Stokes and Minerbo describe a very interesting funneling scheme that employs offset RFQ vanes. With this system it may be possible to increase the brightness of beams by funneling, without introducing significant transverse emittance growth.

Using a 200-MHz RFQ structure to decelerate $\overline{p}$ is an interesting variant that is described in Ref. 58. Antiprotons from LEAR would be decelerated from 2 MeV to 100 keV in a 2-m structure with no significant growth in emittance.

Reference 2 describes how the general theory of RFQ operation can be implemented for improving capture and performance of an electron preinjector.

A 0.1% duty factor, 5-mA, 2.0-MeV RFQ employing stripping of its output H^- beam to H° is being considered as a calibration device for the L3 experiment on LEP.

Discussion

The RFQ structure is based on a mature technology that incorporates many different geometries. Each geometry has its own attributes for particular applications. The obvious advantage of any RFQ is the ability to accelerate a large fraction of a low-energy dc beam without excessive emittance growth or halo generation.

Radio-frequency quadrupoles are in operation throughout the world with good performance records and a promise of interesting future applications. Development of the RFQ worldwide is a good example of concentrated local developments that have led to excellent communication and collaborations. Improvements, modifications, and new technology were quickly assimilated and incorporated into the most recent devices.

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