25 YEARS OF TECHNICAL ADVANCES IN RFQ ACCELERATORS*

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Abstract

The radio frequency quadrupole (RFQ) accelerator began as "The ion linear accelerator with space-uniform strong focusing" conceived by I. M. Kapchinskii and V. A. Teplyakov[1]. In 1979, R. H. Stokes, K. R. Crandall, J. E. Stovall and D. A. Swenson[2] gave this concept the name RFQ. Shortly after Valentine's Day in 1980 a telegram was sent to I. M. Kapchinskii. It stated, "The RFQ is alive and well at the Los Alamos Scientific Laboratory". Thus begins a very informative story of the early history of the development of the RFQ[3]. By 1983, at least 15 laboratories throughout the world were working on various RFQ designs. H. Klein wrote an excellent review of a number of different RFQ structures[4]. In the early years, there were many types of geometry considered for the RFQ, but only a few types have survived. The two cavity geometries now used in almost all RFQs are the 4-vane and 4-rod structures. The 4-vane structure is the most popular because its operating frequency range (80 to ~500 MHz) is suitable for light ions. Heavy ions require low frequencies (below 200 MHz). Because the 4-rod structure has smaller transverse dimensions than a 4-vane RFQ at the same frequency, the 4-rod RFQ is often preferred for these applications. This paper will describe how the RFQ accelerates and focuses the beam. The paper also discusses some of the important technical advances in designing and building RFQs.

RFQ DESCRIPTION

The RFQ has 4 electrodes with alternating RF voltage impressed on them. The dominant characteristic of the electric field is that of a quadrupole shown in Figure 1. A beam of ions traveling down the axis of an RFQ, with a cross section similar to that shown in Figure 1, sees alternating focusing and defocusing electric quadrupole fields. Because the fields oscillate at the frequency of the RF, and are spatially continuous along the axis of the RFQ, the focusing force does not depend on the velocity of the ions. By modulating the radius of the pole tips, a longitudinal electric field can be obtained with the same energy ion beam while bunching and accelerating. Figure 2 defines some of the typical parameters that describe the geometry of the RFQ pole tips. Beta "β" is the velocity of the ions in units of "c," the speed of light, and "λ" is the free space wavelength of the RF Frequency. The modulation factor is "m" and "a" is the minimum distance from the pole tip to the RFQ axis. The gap voltage between adjacent vanes is "V". It is apparent from looking at Figure 2 that the voltage on the axis is tending toward +V/2 at the position indicated with "a". Not shown in figure 2 are the horizontal vanes that have their minimum distance from the axis of "a" where the vertical vanes are "ma" from the axis. Figure 3 shows how the horizontal vanes are offset from the vertical vanes by one cell length. The voltage on axis at the position marked "ma" is tending toward –V/2. Thus there is a longitudinal electric field on axis that peaks half way between "a" and "ma" in Figure 2. The "unit cell" in the RFQ is defined in Figure 2 by βλ/2.

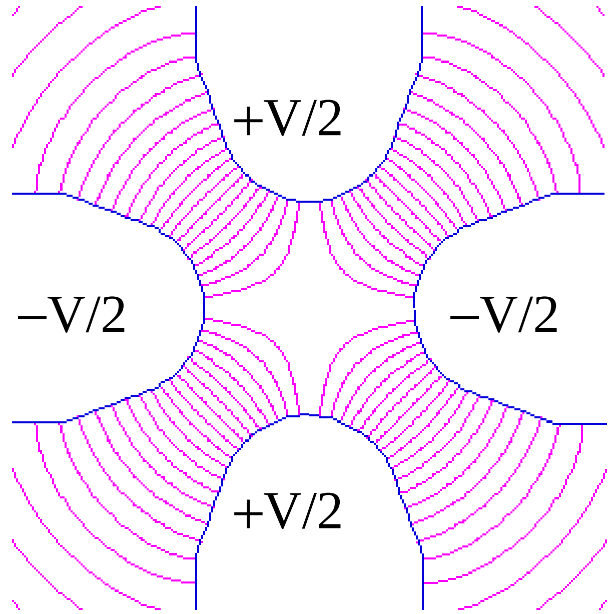

Figure 1: Electric field lines in a RFQ.

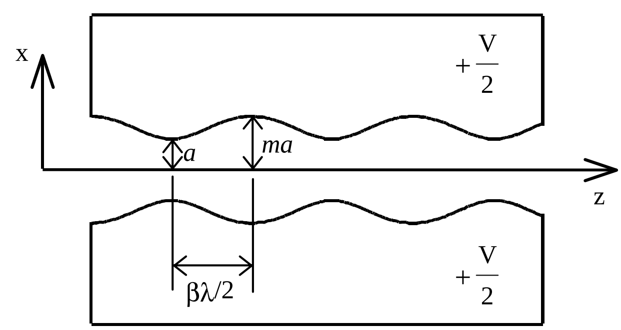

Figure 2: RFQ pole-tip geometry. This figure shows the two opposing vertical electrodes that have the same voltage +V/2. The modulations of the -V/2 horizontal electrodes are shifted by βλ/2 in Z. The length of a unit cell is βλ/2. The modulation is defined as "m".

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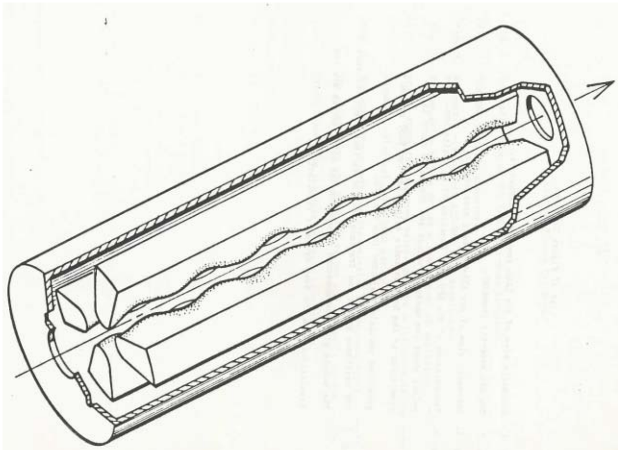

Figure 3: Illustration of modulated vanes in a RFQ showing how the modulation of the horizontal vanes is offset one unit cell from the vertical vanes.

PARMTEQ

Almost as important as the invention of the RFQ was the development of the computer code Parmteq that simulates the beam in the RFQ. K. Crandall modified a version of Parmila and called it Parmteq (phase and Radial Motion in Transverse Electric Quadrupoles)[5]. Parmteq performed the basic functions of designing an RFQ. It generated a physical description of the RFQ, then generated an input particle distribution, and transported the beam through the RFQ. Parmteq also generated output distributions and graphical representations of the beam. This code and local variations were used at most laboratories through out the world and became a standard reference for RFQ simulation.

THE FIRST RFQ

In April-May of 1975 a 4-rod RFQ was started up at the Institute of High-Energy Physics in the USSR[6]. This RFQ operated at 148.5 MHz. The maximum accelerated proton beam current was 140 mA at 1.97 MeV. The normalized emittance was less than 2.5 micron (for 85% of the particles). The pulse length was 10 μsec at 25 Hz.

THE POP EXPERIMENT

The first successful test of a 4-vane RFQ occurred in 1980[7] with the proof of principle (POP) experiment at Los Alamos. A picture of the POP RFQ appears in Figure 4. This RFQ had several features that are still used in modern 4-vane RFQs. The desired operating mode is the TE_{210}. This means the fields are transverse electric (TE). The (21) means that in cross section the fields are quadrupole. The zero (0) means no variation in fields along the axis. In this RFQ, to make the fields uniform the vanes have an undercut on the vane ends. These undercuts are just visible in Figure 3. The end plates in POP had small button tuners opposite the ends of the vane tips. These tuners were used to fine-tune the field flatness. The magnetic field in the TE mode is longitudinal and the flux, which alternates direction in adjacent quadrants, must have a way to turn around at the ends of the RFQ. Without the undercuts, the end pieces would short out the electric field and the electric fields would be zero at the ends. Then the lowest frequency quadrupole mode would be a TE_{211} mode. This type of structure will also support the TE_{11n} modes (where n=0, 1, 2, …) also known as dipole modes. The frequencies of the dipole modes are not too much different from the quadrupole modes.

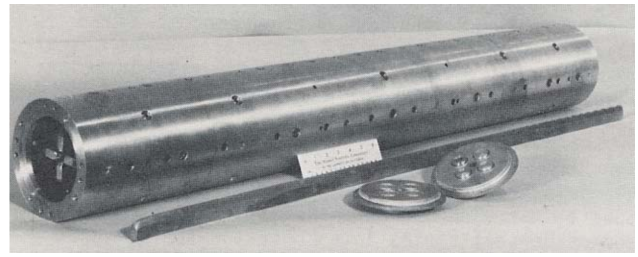

Figure 4: A picture of the POP RFQ experiment.

Beam dynamics issues

The RFQ can take an intense DC beam from an ion source, bunch it, and accelerate the beam to high enough energy to be accelerated by a conventional linac. Therefore, the RFQ must accept beam from a beam line that has static focusing. Whereas the focusing in the RFQ is time varying. The section of the RFQ that accepts the injected beam is called the radial matching section (RMS). The aperture at the leading end of the RMS is quite large and slowly decreases in a prescribed manner[7,8] to the aperture of the next section. The RMS is typically 2 to 5 βλ long. As the beam traverses the RMS the RF time varying focusing increases slowly, conditioning the beam to the time varying focusing channel of the RFQ. With the code TRACE2D[9] a beam from a static transports system can be matched to the RFQ with a RMS. The next section in the RFQ is called the "shaper". In the shaper the modulation "m" starts at 1.0 and increases linearly with z, the position along the axis. The synchronous phase at the start of the shaper is –90 degrees and it also increases linearly with z. The designer can chose the length, final modulation, and final synchronous phase so that the beam distribution has the appropriate shape for the next section which Kapchinskii called the "gentle buncher." In the "gentle buncher" two conditions are imposed: the average length of the bunch is held constant and the small amplitude longitudinal frequency is held constant. These conditions determine "m" and the synchronous phase in the "gentle buncher." The RFQ designer picks the final energy and final synchronous phase of the "gentle buncher." The last section is the accelerator, where in early designs the modulation "m" increases to a maximum practical value of about 2, and the synchronous phase was held constant. The length of the accelerator section depends on the required final energy. These beam-dynamics design philosophies are common to both 4-rod and 4-vane RFQ's.

DIPOLE SUPPRESION

The 4-vane RFQ has pole tips with a gap of only a few mm between the adjacent tips. Under these circumstances the frequency separation between the TE_{21n} and TE_{11n} modes becomes quite small. Depending on the length of the structure, one of the TE_{11n} modes may be very nearly degenerate with the TE_{210} mode. Small perturbations can cause these modes to mix with the TE_{210} mode and distort the fields. On the POP RFQ it was thought that direct excitation from the drive frequency could also excite the nearby TE11n modes and distort the fields. It was for this reason that a coaxial manifold was used to feed RF power to the POP RFQ and several other early RFQs[10,11,12]. Resonant coupling loops were used to transfer power from the coax manifold to the four quadrants of the RFQ providing symmetric power to drive the TE_{210} mode but with negligible coupling to TE_{11n} modes.

Vane coupling rings

The first effective technique used to eliminate the effect of these TE11n modes occurred at Berkeley[13] with the invention of the vane coupling rings (VCR). Vane coupling rings short opposite vanes to each other through holes in the adjacent vanes, effectively raising the frequency of the TE_{11n} modes well above the desired TE_{210} mode. These rings, although simple, had some problems associated with them. Mechanically, they were hard to implement, and electrically, parasitic capacitance associated with the VCR's caused dips in the electric field strength. The increased capacitance also lowered the frequency of the TE_{210} mode. Therefore, the use of coupling rings as dipole suppressors was brief.

Stabilizing loops

In 1990, two new methods of suppressing dipole modes were introduced. The π-mode stabilizing loop (PISL)[14] and the loop-coupled TEM lines[15]. PISLs were used in at least two RFQs: A 432-MHz, 3-MeV RFQ for the Japanese Hadron Project[15] and the 402.5-MHz, 2.5-MeV RFQ for the Spallation Neutron Source (SNS)[16]. In the RFQ for SNS, the PISLs raised the frequency of the lowest dipole mode to about 35 MHz above the quadrupole mode and lowered the quadrupole mode by 11 MHz. Topologically, the PISL is similar to the VCRs and, therefore, they also increase the capacitance or reduce the inductance. Because the PISL's are not so close to the vane tips, no significant dips in the electric quadrupole fields occur. The loop-coupled TEM lines were never used.

Dipole tuning posts

The RFQ for the beam experiment aboard a rocket (BEAR)[17] used dipole suppressors similar to that suggested by Vretenar[18]. These stabilizers were mounted on the end of the quadrants such that they did not effect the tuning of the quadrupole modes, but could lower the frequency of the dipole modes. The advantage these stabilizers had were the ease of installation and virtually no effect on the frequency of the quadrupole mode. The stabilizers only changed the frequency of the dipole modes, so one could adjust them to move the frequency of the dipole mode several MHz from the quadrupole mode. The dipole suppressors, coupled with tuners along the outer wall of the BEAR RFQ resulted in electric quadrupole field strength within a few percent of the design. This type of dipole suppressors has been used on a number of RFQs: the ground test accelerator (GTA)[19], the RFQ for the superconducting super collider (SSCL)[20], the continuous wave deuterium demonstrator (CWDD)[21], and the low-energy demonstration accelerator (LEDA)[22,23]

RFQ BEAM DYNAMICS CODES

PARMTEQ was the first of the RFQ beam-dynamics codes. A number of variations of the code were developed at various laboratories during the early years, but PARMTEQ was the standard with which the other codes were compared. PARMETQ used the two-term potential[2] to calculate the fields for the beam dynamics simulation. In the mid 1980s the code RFQTRAK was being developed at Chalk River[24], This code used higher order multipoles calculated by the code RFQCOEF[25] and used a 3D finite element method to calculate the effects of space charge and image charge. The first use of PARMTEQM, a modified version of PARMTEQ that use the first 8 terms of the RFQ potential, was on the design of the RFQ for SSCL[20]. This RFQ was first designed with PARMTEQ, but it had a much lower injection energy (35 keV) than previous RFQs. A PARMTEQM simulation showed that in this design the transmission was unacceptably low. PARMTEQM was used to redesign the SSCL RFQ and the transmission increased to ~90% for the design current. Simulations of the LEDA RFQ with PARMTEQM and RFQTRAK agreed very well[23].

The newest RFQ simulation codes use the finite difference method to solve for the 3D fields. TOUTATIS[26,27] was used to simulate the LEDA RFQ and the results agreed very well with PARMTEQM and with RFQTRAK, However, there was a very subtle difference in the output distribution. The output distribution from TOUTATIS, when used in simulations of the halo experiment, agreed quite well with the experiment[28]. The distribution from PARMTEQM apparently had fewer particles that ended up in the halo[29]. LIDOIS[30,31] is a package of codes that can optimize the design of the RFQ, then simulate the beam dynamics with fields calculated with the real vane shape.

RESONANTLY COUPLED RFQ

The 8-meter-long LEDA RFQ is comprised of four 2-meter-long RFQ segments resonantly coupled together. The operating mode is the zero mode, meaning all 4 sections are resonating in phase. Figure 5 shows a picture of this RFQ on the tuning table. The idea of resonantly coupling short RFQ together was first expressed in 1990[32]. A 8-meter-long model was built to verify the

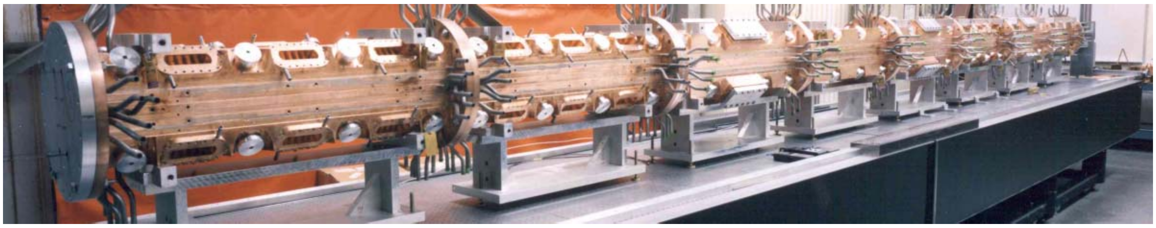

Figure 5: Eight-meter-long RFQ in the tuning laboratory. Adjustable slug tuners can be seen in this picture.

theory[33]. After the successful operation of the LEDA RFQ[34] at least two more Coupled RFQs are being built. The 5 MeV IPHI RFQ is being built at CEA-Scalay[35] and the 5 MeV TRASCO RFQ at INFN-LNL Italy[36]. A 3.5-MeV, 5.7-meter-long coupled RFQ with two sections is being studied in China[37]. In Korea, a 350-MHz, 3-MeV, cw RFQ with two sections coupled together has been built[38].

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