INTRODUCTION TO RFQ SESSION*

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It has been close to 15 years now since our colleagues I. M. Kapchinskii and V. A. Teplyakov[1] in the USSR conceived their "spatially uniform-focusing" idea in the form of practical circuits for focusing and accelerating low-velocity ion beams using electrostatic fields. Almost seven years ago, J. J. Manca[2] whetted our curiosity at Los Alamos by pointing out from Kapchinskii and Teplyakov's work a structure that could capture nearly 100% of an ion beam injected at a few tens of keV/nucleon and accelerate it with little emittance growth to a few MeV. Now the accelerator community at large has realized that a revolution has taken place, and almost everyone is involved. At the 1981 Linac Conference at Bishop's Lodge in Santa Fe, about 17 papers dealt with aspects of the radio-frequency quadrupole (RFQ) structure, as it has also come to be known. At this 1984 conference, there are about 40 RFQ papers, plus discussion at this special session. The aficionados are eager to discuss the latest, but perhaps they will consider a very short review, for those catching up with our enthusiasm, as a context for some remarks on the many challenges of this fundamental and subtle idea that still face the "experts."

Starting with the first crude plastic models (fig. 1) made in an attempt to understand the idea, it becomes clear that a (unmodulated) four-vaned circuit (by establishing a spatially uniform, time-periodic electrostatic quadrupole field along its axis) establishes a strong transverse focusing field that is independent of particle energy (fig. 2). The desired longitudinal actions of bunching and acceleration are accomplished by perturbing the vane edges, or tips, to produce longitudinal fields on the axis (fig. 3).

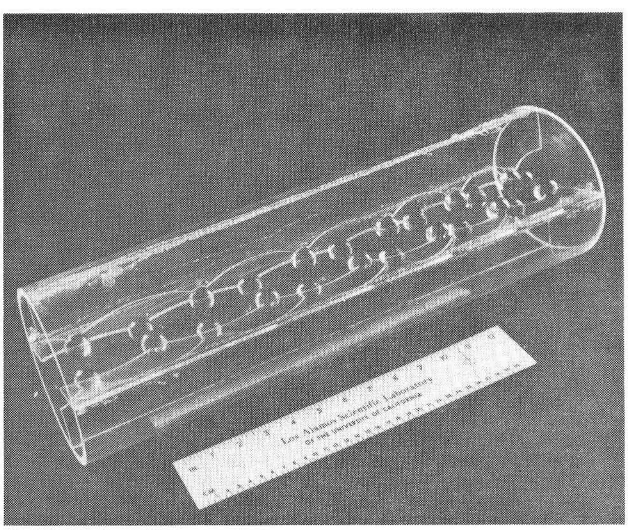

Fig. 1. Original plastic conceptual model.

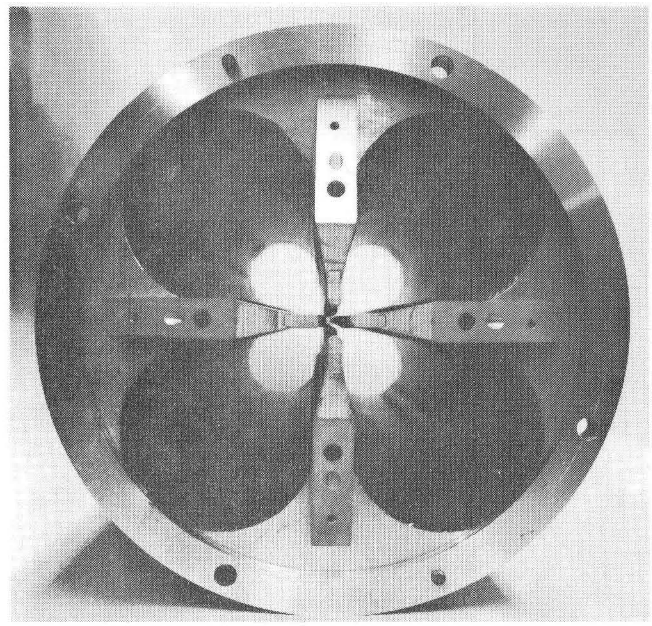

Fig. 2. Early RFQ model.

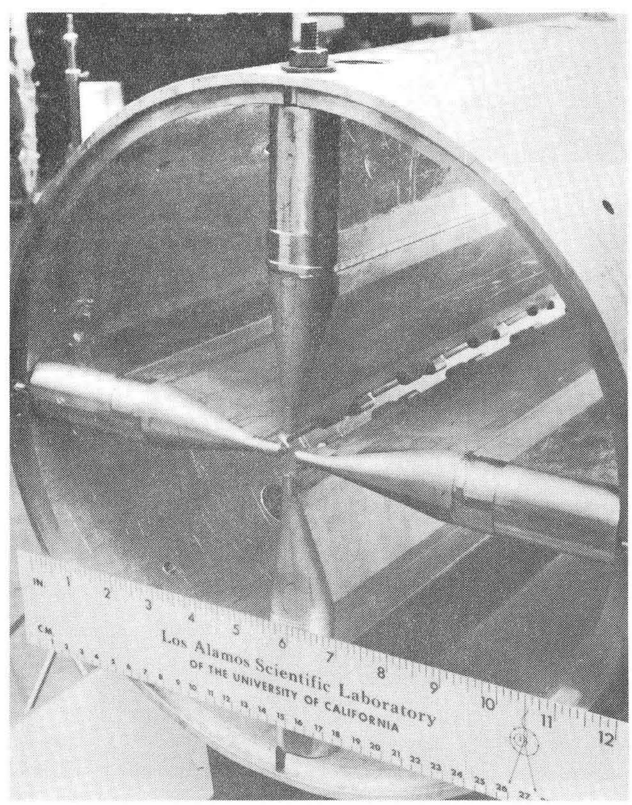

Fig. 3. End view of RFQ with close-up of vane tips.

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From the RFQ field equations (fig. 4), we see immediately that the transverse quadrupole field is directly weakened by the longitudinal perturbation. The fields depend directly on the vane-to-vane rf voltage, $Ve^{j\omega t}$. The transverse-focusing efficiency X is reduced, proportional to the accelerating-efficiency term A that describes the vane and perturbation geometry. As shown in fig. 5, the pole tips ideally will be given a sinusoidal-like variation in radius of ma to a, through a unit cell of length $\beta\lambda/2$. The longitudinal field thus introduced is also favorable for low-velocity particles because the on-axis average accelerating field per cell, $E_0 = 2\Delta V/\beta\lambda$. The energy gain per cell will be $\Delta W = qE_0\ell T \cos\phi$, where $\ell = \beta\lambda/2$ and $T = \pi/4$. We see that introducing the perturbations with a period set by the injected particles could be used to trap and bunch the particles, while an increasing cell length and proper synchronous phase ϕ would cause acceleration.

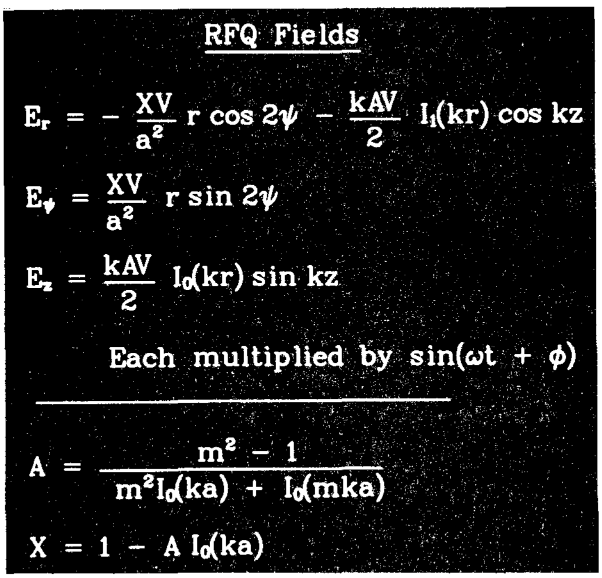


Fig. 4. RFQ field equations.

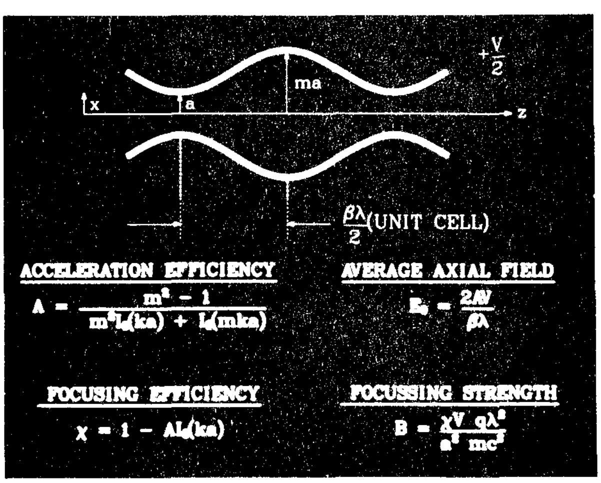
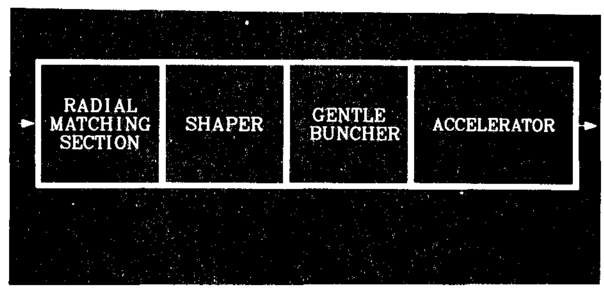


Fig. 5. RFQ nomenclature.

The exciting prospect for nearly complete capture and very high quality bunching and accelerating actions comes from the fact that at the low velocities, $\beta \leq 0.1$, the cell lengths are short enough that many cells (with certain caveats below) can be realized in a structure of practical overall length. In this way, a very old dream of linac builders comes true: with many cells, the action of each cell on the beam can be made gentle--essentially adiabatic, the total parameter variation over all the cells can be complex, and the complicated processes of forming bunches from the dc injected beam and initial acceleration can be performed with minimal degradation in beam quality.

We began to understand, then, that a practical device would have to perform several functions in sequence. As indicated in fig. 6, there needs to be an initial transition from the input beam transport, where the focusing fields are not varying with time, to the RFQ fields. Figure 7 indicates K. R. Crandall's initial invention of an input matching section.



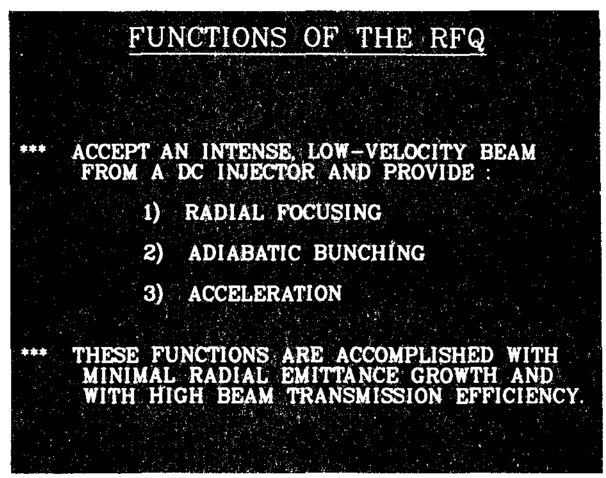


Fig. 6. Functions of the RFQ.

The bunching action was split into two parts. At first, a truly adiabatic bunching action would take too many cells, so longitudinal fields are introduced and increased with z, at $\phi_s = -90°$, in an approximately linear manner that establishes a phase-stable bucket and "shapes" the particle distribution, filling the bucket only to a prescribed level. Next, the gentle buncher, as suggested by Kapchinskii, holds the average z-length of the bunch and the small-angle longitudinal frequency at fixed values. This allows ϕ_s to evolve to the proper value for full acceleration by the end of the gentle buncher, and the particle distribution to be preserved. About a factor of 10 energy increase has resulted at this point. In the accelerator section, the ions are accelerated to the output energy at appropriate ϕ_s.

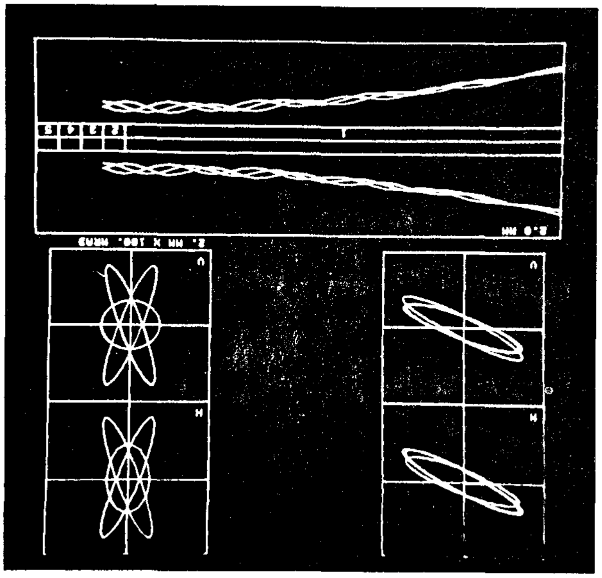


Fig. 7. RFQ input matching section.

Developing the practical tools to make actual hardware required a complete family of computer codes to be written. There are analytic routines for rapid first-order establishment of parameters, and detailed particle-tracking full-simulation codes that include nonlinear, higher order and space-charge effects. These codes are interfaced to rf-structure design codes and to software for numerically controlled milling machines to make the vanes.

The most challenging RFQs made so far are those where intense currents are to be accelerated, and where cw operation is required (FMIT). The linearized saturated transverse and longitudinal current limits can be found analytically; in RFQs of the present generation, the bottleneck occurs at the end of the gentle-buncher section. From typical limit curves as shown in fig. 8, the focusing strength would be chosen where the transverse and longitudinal limits are equal, and the operating current would be 50-60% of the limit value.

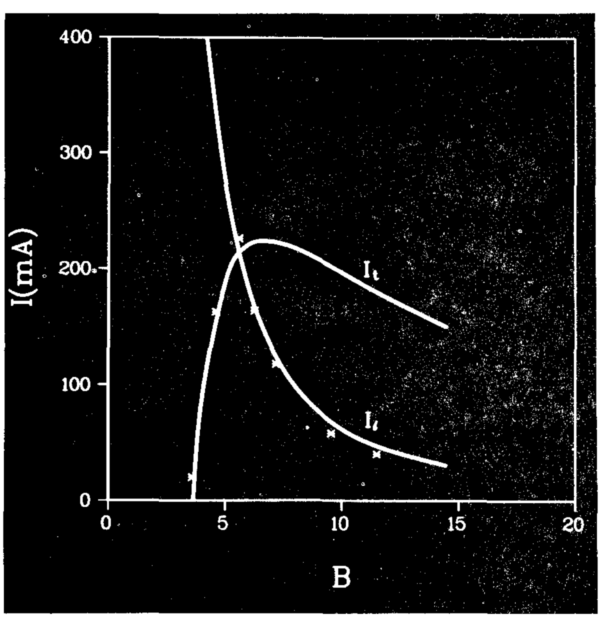


Fig. 8. Current limit versus B.

From fig. 9, we see that other practical limits can come into play. The zero-current transverse phase advance per period, σ_0, should not exceed $\pi/2$ to avoid envelope instabilities. The rf sparking limit has a strong influence on performance--raising the vane voltage is very desirable and the subject of considerable research.

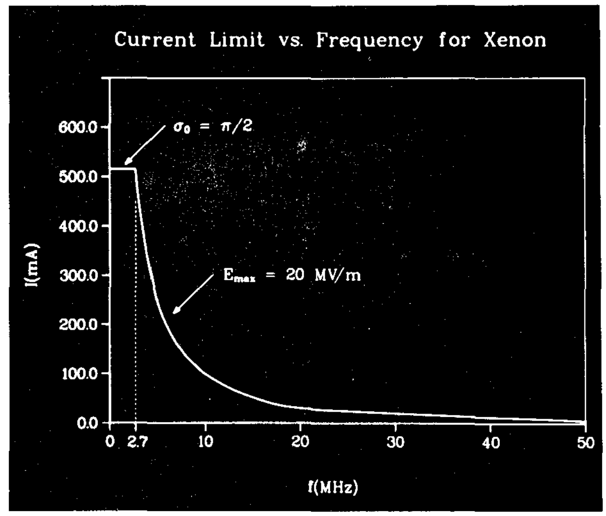


Fig. 9. Current limit versus frequency for xenon.

In RFQs with machined vanes, the structure is immune from the random alignment tolerances that plague the drift-tube linac, and it has been possible to achieve tolerances in vane machining much better than would be required by the beam dynamics. Achieving the proper gradrant-to-quadrant field balance and overall longitudinal-field flatness, on the other hand, has been a challenging problem in maintaining very tight tolerances in these long, noodle-like structures that tend to be mechanically indeterminant. Most of the early practitioners felt uncomfortable without provisioning for some kind of vane positioners that forced some flexibility in the critical rf joints. If the structure becomes too long, the effect of the local vane-to-vane capacitance tolerance results in an unattainable positioning tolerance, as indicated by the formula

$$\frac{\delta V}{V_0} = -\frac{1}{6}\frac{L^2}{\lambda_0^2}\frac{\delta C}{C} ,$$

where it is seen that there is a squared dependence on vane length over electrical wavelength.

This condition makes it advisable to limit the electrical length of a structural unit to about two wavelengths. Even then, very close positioning tolerances are required to prevent unwanted transverse field errors, which can be characterized as the excitation of dipole (steering) modes. This led to the introduction of shorting rings to pin together the voltage of opposing vanes every half-wavelength or so along the structure. This procedure is effective in ameliorating transverse errors, but does not help correct longitudinal tuning errors.

This problem, where prevention of field balance and flatness errors requires tolerances beyond what could be tolerated by the beam dynamics, is at the root of the long-held desire at Los Alamos to provide resonant rf drive coupling from quadrant to quadrant and along the structure. It was this concern that led us to use a coaxial outer manifold to spread the drive around and along the structure, with coupling slots into the RFQ core. Resonant tuning the slots also required very tight tolerances and introduced other concerns, so at present the slots are used in a non-resonant way. Several new ideas for resonant coupling have been envisioned, especially by A. Schempp, and investigation of this possibility will be an important part of future work.

From the earliest tests in the USSR, the experimental performance of RFQs has agreed very well with the theoretical model. (Of course, the theoretical model must include measured fields.) This is not unexpected, given the basic simplicity of the potential function and the way the structure is mechanically assembled. Transition and matching of the beam into the following structure is straightforward, although attention to detail is required, as usual, to insure optimal preservation of quality and insensitivity to current level. This subject is addressed by several papers at this conference, and was demonstrated in the USSR in 1980 or before.

Many interesting questions remain before the RFQ will be considered fully understood; they include the following.

- Attainment of maximum rf voltage
- Attainment of resonant coupling
- Solution of the tuning problems involved in letting the vane-to-vane voltage vary along the structure, which would allow more sophisticated prescriptions for acceleration, bunching, and optimization
- Consideration of multiple tank structures
- Consideration of multiple beam channels arrayed in a single rf and vacuum envelope
- Finding an efficient, practical method of funneling more than one beam together after initial acceleration
- Further consideration of emittance growth minimization
- Structures for very heavy ions
- Consideration of the same principles to find a circuit suitable for low-velocity, high-intensity electron beams

Such questions may stir some debate during this session, and will certainly spur interesting work that will be reported in conferences to come.

References

1. I. M. Kapchinskii and V. A. Teplyakov, "Linear Ion Accelerator with Spatially Homogeneous Strong Focusing," Prib. Tek. Eksp. 119, 19-22 (1970).

2. "High-Current Accelerator Structures," Space Charge in Linear Accelerators Workshop, Los Alamos National Laboratory report LA-7265-C, May 1978, Los Alamos National Laboratory, Los Alamos, New Mexico.