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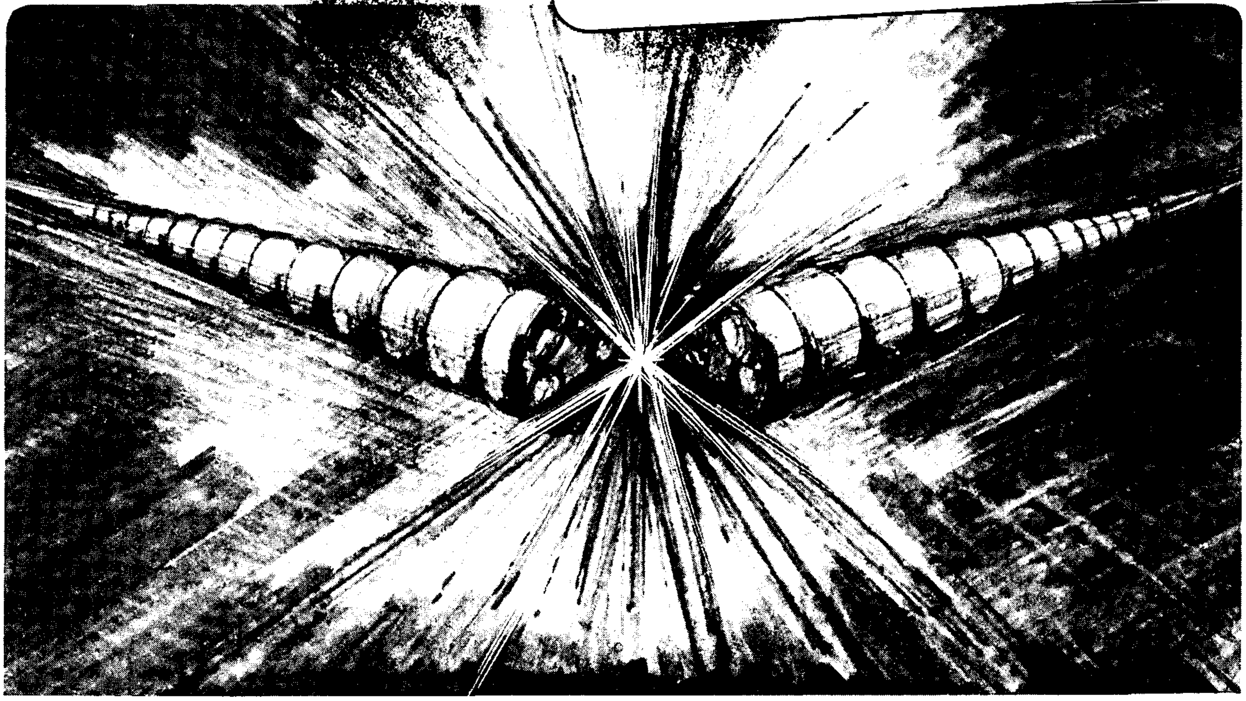

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RFQ Development at LBL*

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Abstract and Summary

LBL's interest in RFQ accelerators goes back to 1978. We have developed, constructed and operated a heavy ion machine that is the central part of an upgrade project in which our old proton injector linac is converted to a light ion injector system. We are now designing a second heavy ion RFQ linac which will be used at CERN for the injection of light ions into the PS complex. Other RFQ accelerators are under study for possible additional projects.

LBL has pioneered new techniques, such as the vane mounting and adjusting mechanism, and the electrical shorting rings which stabilize the cavity field distribution. In conjunction with INS, Tokyo, a new design procedure has been derived, optimized for low current, heavy ion RFQ's which results in a short, efficient structure.

LBL has had considerable operational experience with an Alvarez structure operated at high gradients for several years. As the operational characteristics of an RFQ improve dramatically with surface field, our experience with this operation and its implications for future RFQ linacs is discussed.

Introduction

LBL has been engaged in RFQ research since early 1978. We first became interested in an RFQ accelerator to satisfy the requirement for an efficient pre-injector for the upgrade of a 20 MeV proton linac that has been used since 1971 in the $2\beta\lambda$ mode for acceleration of ions to 5 MeV/n. Typical ion species and intensities obtained with the old injector system are as follows:

Ion	Charge	Current
C	+4	10-20 eμA
N	+5	5
O	+5	5
Ne	+6	0.1

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The q/A of this set of ions ranges from 0.30 to 0.36, requiring high gradients in the linac, with E_0 reaching 3.5 MV/m at the low energy end.

To increase the intensity and the range of available mass species, major modifications are being made to the 20 MeV injector linac[1]. A low charge state PIG ion source is used, producing Si^{+4} for example, to maximize the intensity. A new first stage accelerator consisting of a 200 MHz RFQ linac, designed for a $q/A = 1/7$ follows the ion source and accelerates the beam from 8.4 to 200 keV/n. The beam is then accelerated to 800 keV/n by a new Alvarez accelerator operating in the $2\beta\lambda$ mode for $q/A = 1/7$ at 200 MHz and then stripped to a $q/A > 0.35$ by a foil stripper. The beam is further accelerated in a portion of the original 20 MeV Alvarez linac, which is modified by removing the first 24 drift tubes. As the transit time factors in the remaining part of the original linac are greater than in the front end, the linac is run at a lower gradient than at present. The heavy-ion, high frequency RFQ structure for this modification has been fabricated, constructed, and operated successfully. Representative currents of the heavier ion species are as follows:

Ion	**Charge**	**Current**
Ne	+3	1300 eμA
Si	+4	290
Ar	+6	41

Silicon RFQ

The basic parameters of the Silicon RFQ are as follows:

Design ion	Si^{+4}
q/A	0.143
Frequency	200 MHz
Input energy	8.4 KeV/n
Output energy	200 keV/n
Length	2.24 m
Acceptance	0.05π cm-mrad (normalized)
Transmission	86 %
r_0	0.254 cm
B (focussing)	2.7
E_S	27.2 MV/m
Vane-vane voltage	56 kV

The physics design of this linac began in 1981 at LBL with the assistance of S. Yamada and N. Tokuda, both of INS, Tokyo. The basic design algorithms developed at LASL[2] were used as the starting point, and improvements were made at LBL, focussing specifically on heavy ion, high frequency structures. Yamada developed a technique of optimizing the buncher section of the linac to shorten the overall structure, when space charge is not significant[3]. Tokuda developed an improved treatment of the input radial matching section that treated the longitudinal fringe fields[4].

To match the rapid betatron phase advance of the focussing in the RFQ to the following Alvarez linac, an exit radial matching section was also added to the RFQ[5]. In this section, the value of the focussing parameter B is reduced from 2.7 to 1.8 over a distance of 65 cm, about one betatron oscillation wavelength. This increased the size of the output beam about 10%, and reduced the divergence of the output beam by 15 to 35%. This was sufficient to simplify the matching into the following Alvarez, where the first accelerating gap is 7 cm from the end of the RFQ vane. However, the value of r_0 in the exit matcher increases from 0.254 to 0.312 cm, increasing the local cutoff frequency. This effect is compensated for with the coarse tuners attached to the sides of the vanes maintaining a constant vane voltage.

The mechanical design introduces several new ideas to the construction of RFQ's[6]. Our physics design is based on a 200 MHz structure with an r_0 of 0.254 cm and an overall length of 1.5 free space wavelengths. The small value of r_0 results in a strong sensitivity of field distribution in the cavity to radial and transverse displacements of the vane tips. The relative length of the cavity further enhances the field errors due to vane tip displacements. We approached these problems with a two-pronged attack: the mechanical design of the cavity fixes the vane tip position precisely in an easily adjustable way, and the remaining field errors are reduced by electrical vane coupling rings (VCR's)[7].

The mechanical design of the vane support is based on the principle of supporting each vane on 6 plugs, 40.6 cm apart, inserted through holes in the surrounding cavity. The radial and transverse position of the vane tip in the vicinity of each plug is determined by shims or by machining the surface of the plug. The spacing between the plugs is determined by the strength of the bolt that attaches the vane to the plug and by the flexibility of the vane itself. Approximately 95% of the radial or transverse motion of an individual plug is transmitted to the tip of the vane at the plug location, and about 5% of the motion of a plug is transmitted to the vane tip at an adjacent plug. Thus a nearly independent set of adjustments at 6 points along each vane is possible.

The position of the vane tip is measured from several fiducial marks[5,6], cut at the same time as the modulations, to each other and to precision surfaces on the outside of the cavity. We can measure the transverse and radial position of the tip of a single vane to reference surfaces on the cavity to a precision of 10-15 microns. A vane is mounted in the cavity, and its position is measured. Then a set of shims is prepared for the transverse final positioning, and two surfaces on the mounting plugs are machined for the radial positioning. The stability and reproducibility of the mounting system is such that a vane removed from the cavity and remounted is found to be within 10-15 microns of its original position.

This process is repeated for all four vanes, one at a time. Then groups of two opposing vanes are mounted and checked for vane tip to vane tip separation. All four vanes are then mounted and further checked for relative positioning accuracy. Any errors found, which were small in our case, may be corrected by further adjustment of the shims and plugs.

To achieve less than 5% azimuthal field variation in the four quadrants requires vane tip positioning accuracy of better than 2.5 microns, which is not practical from mechanical considerations. The required azimuthal field variation is achieved by coupling the opposing vanes together, at three places longitudinally, with vane coupling rings (VCR's). At each location, two rings connect the two even vanes together, and two more are used for the odd vanes. The resultant azimuthal field variation is within ±2.5%[8]. The non-zero inductance of the rings prevents a perfect balance. The azimuthal field variation without the rings with the vanes in exactly the same positions was approximately ±25%.

The capacitance between the rings and between the rings and the vanes they pass through cause an additional loading of the cavity, lowering the overall resonant frequency, and in addition cause a local increase in the vane voltage. The overall frequency shift must be determined beforehand so the cavity will resonate at the required frequency with the rings in place. In our case, bulk tuners are fitted to the sides of the vanes, two per vane, to raise the cavity frequency to compensate for the effect of the VCR's.

The vane voltage in the vicinity of each set of rings will be increased relative to the average vane voltage due to the lowering of the local frequency at the VCR's. The voltage variation is proportional to the square of the distance between sets of VCR's. Too few VCR's will perturb the frequency less, but the longitudinal variation will be more. Therefore a compromise is necessary in choosing the distance between the VCR's. In our case, this distance is $0.75\lambda_C$. With a heavily loaded cavity such as ours, the separation should be in the 0.5-$0.75\lambda_C$ range, with a larger spacing allowable in lightly loaded (proton) cavities.

The cavity does not use an r.f. power manifold. The required peak r.f. power of 155 kW is supplied by 3" rigid coaxial cable to one coupling loop in the longitudinal center of the cavity. A fine tuner, a rotatable shorted loop 5 cm in diameter, is located in the center of the cavity in the quadrant opposite the drive loop. The total range of variation in frequency with the fine tuner is 0.1%. Because of the tight azimuthal coupling with the VCR's and the location of the tuner close to a VCR set, no change in field distribution is observed when the fine tuner is adjusted. The absence of an r.f. manifold allows easy access to the cavity and strong coupling to the r.f. power source.

The critical parts of the RFQ were built in our own shops. It was important to include the shop personnel in the original mechanical design process to take advantage of their experience in producing high precision components. In addition, their feeling of being made an important part of the project paid off in the fabrication effort. The performance and interest on the part of the mechanical shop was important in the success of the entire project. Items that were built outside of the laboratory, primarily the outer cavity, were carefully controlled through frequent interaction between our engineers and their personnel.

The RFQ took one year to build. The following table shows the important dates in the construction and testing, as well as modifications to the old Alvarez linac:

1982	June	Begin construction
	October	Vanes finished
	November	Cavity finished
1983	January	Vanes, cavity plated
	March	Vanes assembled into cavity
	May	High power tests, beam tests
	July	End of RFQ tests, RFQ removed
	September	Cockcroft-Walton removed
	November	20 MeV linac drift tubes removed
	December	New holes in Alvarez tank for new drift tubes

The assembly of the cavity and the low level r.f. tuning took about two months. Some of this time was devoted to the finishing of the end plates and mounting the RFQ in the test stand. The complete high power and beam tests took about six weeks. At this point, the RFQ had proven itself to be a good performer and was removed, making way for the start of the modifications of the 20 MeV Alvarez linac. The Cockcroft-Walton preinjector was completely removed, as were the first 24 drift tubes from the Alvarez. At the beginning of 1984, the new Alvarez prestripper linac and ion source and transport systems will be installed, and the RFQ will be moved to its final location.

RFQ Operation

The RFQ is a remarkably good performer[9]. The r.f. conditioning period was just a few hours. The beam was successfully accelerated on the first try after the required gradient was achieved, which was on the second day of operation. The multipactoring levels all disappeared except one, at 31% of full gradient. The transmission was about 75% of the calculated transmission, which may be attributed to two causes: the emittance of the input beam beam was not well known but was most likely larger than desired, and the beam was matched into the RFQ with a lens of four quadrupoles, which is difficult to tune correctly. In retrospect, a magnetic solenoid may have been a better input focussing device. A smaller emittance beam was accelerated at the calculated transmission.

The measured Q of the cavity of 6000 was approximately one-half of the theoretical Q. This is similar to the values observed for some other RFQ's. In our case, there are many r.f. joints in the azimuthal current path. Each quadrant contains two joints to the wall, made with a silver-plated stiff spring. There are also two coarse tuning bars, each with two spring finger stock r.f. joints. Therefore there are a total of 24 joints in series with the azimuthal r.f. current path in the RFQ. We believe that these joints are responsible for most the the additional losses that reduce the Q to one half of the theoretical value. Given the actual measured value of the Q, along with the fact that the the A_{10} component, of the synchronous accelerating wave, is 93% of the value A used in the design, the r.f. power requirement for acceleration is in agreement with the observed value.

The cavity is machined from mild steel and then plated with copper to a thickness of 5 microns[6]. The plating process uses a 0.5 micron cyanide copper strike followed by an acid process copper plating. As the variation of thickness of copper at the vane tips could be large, only the cyanide strike was used at the vane tips. Tests on plated specimens show that eventually the copper will be sputtered away from the high field region. After six weeks of operation, the high field region of the vane tips shows considerable darkening with many small pock marks uniformly distributed, but no degradation in Q. In fact, the Q increased slightly during the period of operation. The total stored energy in the cavity is 0.6 joule, well below the level of spark induced surface damage.

After several weeks of operation, no spark damage between the rings and the holes in the vanes through which they pass is observed. A considerable amount of sparking is seen between the vane tips. The design surface field for our machine is 27 MV/m (1.85 Kilpatrick), but the maximum value is closer to 29 MV/m (2.0 Kilpatrick). This field was achieved after only a few hours of operation with a $8\text{-}10\cdot10^{-7}$ Torr vacuum. The vacuum with r.f. off finally settled to $3\text{-}4\cdot10^{-7}$ after a few weeks, essentially the design value.

The RFQ-Alvarez combination requires that the Alvarez linacs operate in the $2\beta\lambda$ mode, providing 5 MeV/n ions to the synchrotron. For proton beams, this may not be satisfactory, as the quality of the Bevatron guide field at the low value required for 5 MeV injection is poor. If a proton beam of 800 keV were available, the two Alvarez linacs could be run in the $\beta\lambda$ mode for a final energy of 20 MeV. The present RFQ cannot provide 800 keV protons, as that velocity is not synchronous with the structure. However, the RFQ is an excellent non-accelerating transport channel as a non-synchronous beam will not interact with the longitudinal fields in the structure. An externally generated 800 keV proton beam (produced, for example, by another RFQ) can be drifted through the present RFQ with only a negligible amount of energy spread, less than ±2%, added to the beam. We also drifted a low energy heavy ion beam through the RFQ non-synchronously. No energy spread was observable down to the ±0.2% resolution of our spectrometer. In general, a beam can be transported through an RFQ without significant energy spread being added if the beam is not synchronous with the accelerating harmonic of the longitudinal field. This may have applications for other uses.

Oxygen RFQ

The next RFQ to be constructed at LBL is a small device that will be used at CERN to inject an oxygen beam into the PS/SPS complex. This will be part of a collaboration between four laboratories: Grenoble will supply an ECR ion source supplying O^{+6} at an energy of 5.63 keV/n. GSI will supply the transport and matching system between the ion source and the RFQ. LBL will supply the RFQ that will accelerate the oxygen to 140 keV/n, the input energy for the CERN Linac I operating in the $2\beta\lambda$ mode. And CERN will supply the rest of the accelerator facilities. The beam will be supplied, at PS energy, to the streamer chamber and to the plastic ball, both located in interaction regions of the SPS. Physics runs are scheduled to begin in 1986. All of the parameters given here are tentative: the design has not yet been completed.

The basic RFQ mechanical design will be essentially identical to the successful design of the silicon RFQ. The most important difference is the shorter length of 86 cm. This will ease the design of the pumping system. The silicon RFQ uses four cryopumps, one on each quadrant, located approximately 1/3 from the end. The oxygen machine is about 1/3 as long as the silicon machine, and we may pump it entirely from one end with one pump.

The physics design of the machine is quite a bit different from the silicon machine. The transverse acceptance requirement is 0.10π cm-mrad, normalized. This large number has had a strong effect on the selection of parameters. One important parameter is the size of the cutting tool that is used to machine the modulations into the vanes. The size of the tool is determined by the minimum longitudinal radius $\rho_\parallel$ along the vane tip at the end of the gentle buncher section. Using the same general values of the focussing parameter B and surface field E_S as for the silicon RFQ produces a vane tip with such a small longitudinal radius of curvature that it cannot be machined.

We have therefore adopted an entirely new design with a large value of B and a small value of E_S. A summary of important preliminary parameters is given below:

Design ion	O^{+6}	
q/A	.375	
Frequency	202.56	MHz
Input energy	5.63	keV/n
Output energy	140	keV/n
Length	0.86	m
Acceptance	0.09π	cm-mrad (normalized)
Transmission	97%	
r_0	.225	cm
B (focussing)	7	
E_S	22.6	MV/m
Vane-vane voltage	35.6	kV

The combination of low E_S and high B gives a relatively large acceptance and a minimum longitudinal radius that allows the use of a large (0.95 cm radius) cutting tool. However, the large value of B implies a short betatron wavelength and a very divergent output beam. Therefore an exit radial matcher will be included in this machine. It will be about one betatron oscillation long, or about 20 cm, and B will taper down to a value of 4. In the exit radial matcher, r_0 will increase from

0.225 to 0.305 cm, causing a local frequency variation over the last 23% of the machine. Local tuners will compensate for this effect.

As the machine is $0.57\lambda_C$ long, the cavity fields are 7 times more stable against tuning errors than the $1.5\lambda_C$ long silicon machine. To reduce field errors, to allow one drive loop and one fine tuner to be used, VCR's will be used in this machine. We expect that a two sets of rings will be used, one set at each end of the machine with none in the middle, which is less accessible. As with the silicon RFQ, no end tuners will be used, reducing the distance to the beam focussing devices located at each end of the machine.

The ECR source will supply 8-15 pμA of O^{+6} to the RFQ. This will be accelerated to 140 keV/n by the RFQ and injected into the CERN Linac I operating in the $2\beta\lambda$ mode at a gradient approximately 55% above the normal proton value, a level which has already been proven. Some 5 to 15% or possibly more of the original source current will be available at the end of the linac for injection into the PSB with a 100 μsec pulse. The accumulated beam will then be transferred to the PS for acceleration. We expect that approximately 10^9 ions per pulse will be available at the experiment.

RFQ Parameter Sensitivity

It is interesting to investigate the sensitivity of the RFQ design to variation of the primary parameters. This eases the task of optimization of the machine relative to conflicting requirements. We find that a higher surface field improves most characteristics of the RFQ with one notable exception: the minimum longitudinal radius decreases so the machining of the modulations becomes difficult or impossible.

There are several ways to design the basic cell structure of an RFQ. At LBL we use two methods: The Yamada-Tokuda technique, and the original method developed at LASL using the RFQUIK program[2,10]. We use the Yamada-Tokuda method for our heavy ion, low current designs, and then check them against the LASL method. It is instructive to derive the parameter sensitivity of both methods and compare them.

The independent variables for the design are the input energy T_{IN}, the operating frequency f_0, the stable phase at the end of the machine Φ_S, the surface field E_S, the focussing strength B, and the charge to mass of the ion q/A. The Yamada-Tokuda method also requires that the transverse acceptance be specified as an independent parameter, the LASL method determines the acceptance as a dependent parameter. We developed a matrix of the logarithmic derivatives of all the dependent parameters as a function of the independent parameters for the CERN O^{+6} machine using both design techniques. The values in the matrix are the power that a dependent parameter depends on an independent parameter.

Yamada-Tokuda (GENRFQ) method

Dependent parameters

		V	r_0	L_{TOT}	$\rho_\parallel$	k	I_T	I_L
	T_{IN}	–	–	–	1.0	−.1	−.3	.8
	f_0	−1.3	−1.8	.8	−.5	−.1	−1.7	−3.0
	$\lvert\phi_S\rvert$	–	–	.4	–	–	–	–
independent	E_S	2.0	.9	−3.6	−1.0	.1	3.5	1.2
parameters	B	−1.2	−1.2	.9	2.1	−.3	−3.5	−1.3
	q/A	1.1	1.1	−2.2	−1.0	.2	3.1	–
	Accept	–	–	.7	–	–	–	–

LASL (RFQUIK) method

Dependent parameters

		V	r_0	L_{TOT}	$\rho_\parallel$	k	I_T	I_L	Accept
	T_{IN}	–	–	.9	2.3	−.2	−.4	2.0	–
	f_0	−1.3	−1.7	.3	1.6	−.3	−1.4	−.2	−2.4
	$\lvert\phi_S\rvert$	–	–	4.6	−1.0	–	.3	.8	–
independent	E_S	2.0	1.0	−2.0	−3.5	.3	2.1	5.6	1.6
parameters	B	−1.2	−1.2	1.0	3.0	−.5	−.4	−1.7	−1.1
	q/A	1.0	1.0	−1.8	−2.9	.3	1.2	.3	1.9

We see, for example, that the vane voltage V, a dependent parameter, depends on the -1.3 power of the frequency f_0 for both machines. Very important independent parameters are the operating frequency f_0, the surface field E_S, and the focussing parameter B. For a high current limit, the frequency must be low, the surface field must be high, and the focussing parameter B must be low. The necessity of a low focussing parameter for a high current limit is at first not an obvious result. However, many other variables are also determined by the value of B which also affect the current limit indirectly. This is an example of the non-intuitive coupling of parameters in the design of an RFQ. For this reason, no one standard design technique has been established for RFQ's, unlike design of Alvarez machines.

We see that raising E_S or lowering B to increase the acceptance and current limit reduces the minimum longitudinal radius $\rho_\parallel$ along the vane, reducing the size of the cutter used to cut the modulations. The cutter must be larger than a minimum radius of 0.5-1 cm for mechanical stiffness, sufficient surface velocity, and surface smoothness with a reasonable step between passes of the cutter. This requirement for a large $\rho_\parallel$ is in direct conflict with the need to maximize the acceptance and current limit. Our solution was to increase the value of B and reduce the values of E_S so that a reasonable cutter could be used (0.95 cm radius) and sacrifice the acceptance and current limit of the machine. To increase the acceptance and current limit while maintaining an adequate cutter size, the operating frequency must be lowered. This was not acceptable in the case of our RFQ's, where the frequency was fixed.

As the operating frequency of the structure is lowered, the conventional four-vane structure becomes large. The LASL FMIT RFQ, an 80 MHz structure, is a good example of this. For large acceptance and current limit, a different structure is required, such as the those of Müller[11] or Klein[12].

The sample machine designed with the RFQUIK program is similar to the machine designed with GENRFQ with the notable exception that it is longer, 131 cm instead of 86 cm, and that the longitudinal current limit is 9.3 emA instead of 4.5 emA. The bunching action in the shorter machine proceeds more quickly, and a shorter bunch is produced at the end of the buncher, reducing the space charge limit. The current from the ECR source is approximately 50 eμA, or about a factor of 100 less than the space charge limit of the GENRFQ machine.

High Gradient Alvarez Operation

High gradient operation of RFQ's dramatically improves their acceptance and space charge limit. Present RFQ's are designed with a surface field of up to 2 Kilpatrick, 29 MV/m for a 200 MHz machine. The AT-2 RFQ at LASL has been operated to more than 3 Kilpatrick during tests. Other than this, no real experience has been accumulated for high gradient operation in ion linacs at these frequencies, but our experience with an Alvarez may be indicative.

We have had 12 years of experience with high gradient operation of the 20 MeV injector linac in the $2\beta\lambda$ mode. The transit time factors in the front of the tank in the $2\beta\lambda$ mode are 42% of the $\beta\lambda$ values. In addition, ions with q/A down to 0.30 are accelerated. The tank was tilted 10% from the $\beta\lambda$ mode, where the average gradient E_0 is 2.0 MV/m, resulting in a gradient at the beginning of the tank of 3.5 MV/m and 3.2 MV/m at the high energy end. The average gap field at the front end is 1.2-1.3 Kilpatrick and the total stored energy is 125 joules.

It has been our experience that about two weeks of conditioning is required to achieve this gradient. After conditioning, the machine is relatively stable, but experiences deconditioning after a quiescent period. The machine originally used diffusion pumps, resulting in organic materials being deposited inside the tank. Several years ago, those pumps were replaced with ion and turbomolecular pumps.

When the linac was recently decommissioned, we noticed that the first two drift tubes had considerable damage to their faces, from the bore hole to the outer diameter, in the form of a rough surface. The rest of the drift tubes exhibit a multipactoring pattern, matching the focussing quadrupole field, but no surface damage. Copper dust was found lying at the bottom of the machine at the entrance end, evidently the result of sputtering and spark damage of the drift tube surfaces. Operation at 1.7 times the original design gradient is possible, but in our case resulted in slow physical damage to the structure.

This development work owes its success to the efforts of S. Abbott, R. Gough, D. Howard, H. Lancaster, R. MacGill, R. Richter, H. Schneider, N. Tokuda, S. Yamada, E. Zajec, and many others whose work is gratefully acknowledged.

References

1. S. Abbott, D. Brodzik, R. A. Gough, D. Howard, H. Lancaster, R. MacGill, S. Rovanpera, H. Schneider, J. Staples, R. Yourd, "RFQ Development at LBL", Proceedings of the Seventh Conference on the Application of Accelerators in Research and Industry, Denton Texas, Nov 1982
2. K. Crandall, R. Stokes, T. Wangler, "RF Quadrupole Beam Dynamics Design Studies", 1979 Linear Accelerator Conference, Montauk, Sep 1979
3. S. Yamada, "Buncher Section Optimization of Heavy Ion RFQ Linacs", Proceedings of the 1981 Linear Accelerator Conference, Santa Fe, Oct 1981
4. N. Tokuda and S. Yamada, "New Formulation of the RFQ Radial Matching Section", Proceedings of the 1981 Linear Accelerator Conference, Santa Fe, Oct 1981
5. J. Staples, "Beam Dynamics and Vane Geometry in the LBL Heavy Ion RFQ", Proceedings of the 1983 Particle Accelerator Conference, Santa Fe, March 83
6. S. Abbott, R. MacGill and R. Yourd, "Mechanical Design of a Heavy Ion RFQ", Proceedings of the 1983 Particle Accelerator Conference, Santa Fe, Mar 1983
7. D. Howard and H. Lancaster, "Vane Coupling Rings: A Simple Technique for Stabilizing a Four-Vane Radiofrequency Quadrupole Structure", Proceedings of the Seventh Conference on the Application of Accelerators in Research and Industry, Denton Texas, Nov 1982

   H. Schneider and H. Lancaster, "Improved Field Stability in RFQ Structures with Vane Coupling Rings", Proceedings of the 1983 Particle Accelerator Conference, Santa Fe, Mar 1983
8. H. Lancaster, R. Gough, D. Howard, H. Schneider, "Vane Coupling Rings Simplify Tuning of the LBL RFQ Accelerator", Proceedings of the 12th International Conference on High Energy Accelerators, Aug 1983
9. J. Staples, R. Gough, H. Schneider, E. Zajec, "Initial Operation of the LBL Heavy Ion RFQ", Proceedings of the 12th International Conference on High Energy Accelerators, Aug 1983
10. T. Wangler, private communication
11. R. Müller, U. Kopf, L. Funk, "Heavy Ion RFQ Status Report", GSI Scientific Report 1982
12. A. Schempp, P. Junior, H. Klein, M. Daehne, M. Ferch, K. Langbein, Z. Zoubek, "Status of the Frankfurt Zero-Mode Proton RFQ", 1983 Particle Accelerator Conference, Santa Fe, Mar 1983

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