Title
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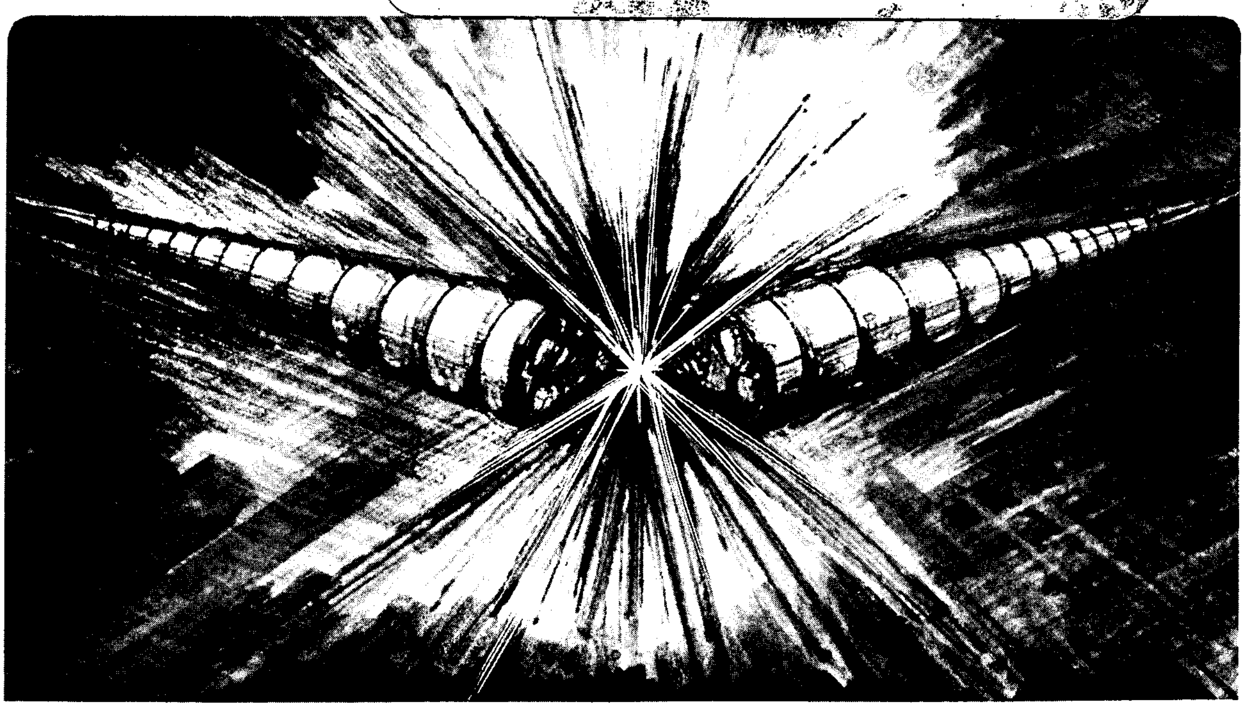

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RFQ's in Research and Industry

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Abstract

The Radio Frequency Quadrupole accelerator (RFQ) has now matured to the point where it has found wide application. Many machines are in use as part of a synchrotron injector chain with others in unique and unusual applications. Several new RFQ's are now under construction or operating since the last survey. They are of various configurations, making use of various techniques of fabrication and field stabilization. Duty factors are being pushed up, new beam dynamics design techniques are be used and emittance blow up mechanisms are better understood. Finally, RFQ's are moving from the laboratory to the commercial marketplace.

Introduction

The RFQ is fundamentally a focusing channel with acceleration introduced as a perturbation. This permits an arbitrary configuration of the longitudinal field, allowing adiabatic longitudinal capture and optimization of the beam dynamics in all three phase planes. The short focussing cell size, unimpeded by the minimum practical length of a discrete quadrupole as in a drift tube linac, allows low energy injection, while the long bunch length at the beginning of the adiabatic compression process maintains a high space charge limit. In the nearly 20 years since the RFQ principle was discovered by Kapchinskii and Teplyakov[1] many practical forms of the accelerator have been developed for various applications.

This paper will continue the spirit of the review papers by Klein[2] and Schriber[3]. New machines and applications will be emphasized, and individual topics of particular interest to the RFQ designer and user will be covered. The reader is referred to the paper of Crandall et al.[4] for the theory of RFQ operation and notation used in this paper.

New RFQ's

At this date, approximately 50 RFQ's are in operation, under construction, or are under serious consideration. The widest variety of machine development is taking place at LANL and at IAP in Frankfurt. Some novel uses are appearing such as the use of an RFQ at LEAR to decelerate an antiproton beam and another one also at CERN to calibrate the BGO crystal array on the LEP L3 detector. Many of the new RFQ's will serve as injectors to synchrotrons, and others will accelerate heavy ions from a hot production target (TRIUMF) and serve to test the propagation of a 1 MeV beam in the exosphere (LANL).

LANL

LANL is currently operating the 425 MHz 2 MeV AT-2 machine which recently successfully injected a 5 MeV DTL. The 80 MHz FMIT RFQ has now been shut down after an informative period of operation in the long pulse and cw mode where the effects of high r.f. and beam power levels were fully appreciated. Both of these machines were driven from a coaxial manifold. The FMIT machine experienced serious multipactoring problems until the electron multiplication coefficient of the surface was reduced by an application of a TiN coating[5]. Some trouble was experienced with overheating of the r.f. gaskets on the vane base and the piston tuners. The beam itself developed a halo which could melt a metallic object several standard deviations from the core.

In addition to the construction and testing of prototypes of four rod and spiral structures and a short four vane sparker, a significant new RFQ has been designed by LANL for the BEAR project and will be built by Grumman[6]. It will test beam propagation at 1 MeV in the exosphere. This 425 MHz machine that delivers approximately 20 mA of H^- with a 0.025% duty factor will be launched on a rocket to an altitude of 205 km and then recovered. Two 60 kW solid state power modules will each drive the RFQ with its own coupling loop, located in diametrically opposite quadrants.

This machine will be constructed of 6061 aluminum vanes with only four joints with copper plating up to the vicinity of the vane tips. After tuning, these joints will be covered over by electroformed copper. In a sparker test cavity, 6061 aluminum vanes achieved a peak surface field in short pulse operation of 3 kilpatrick, about 59 MV/m; the RFQ runs at a surface field of 1.875 kilpatrick.

Of particular interest is the beam dynamics design, developed by Wangler[6], which minimizes the power requirement and output energy spread. This design lengthens the shaper and shortens the gentle buncher, with a stable phase of –40° at the end of the buncher. The larger bucket and longer bunch length increases the space charge limit over conventional designs, allowing the injection energy to be lowered, shortening the machine and reducing the power requirement. The larger bucket appears to linearize the longitudinal motion of the bunch, which together with the lower injection energy, lowers the energy spread of the accelerated beam.

Another new RFQ at LANL will be the GTA-1 machine, a 2 MeV machine similar in beam specifications to the AT-2 machine, and industrially manufactured. This machine will be loop driven and enclosed in a vacuum manifold.

IAP, Frankfurt

Klein's laboratory is developing a wide range of RFQ types. The four vane HERA injector is under construction, along with a four rod equivalent, a 49 MHz split coaxial resonator (SCR) heavy ion RFQ, spiral supported four rod structures, and the 50 and 400 MHz European Hadron Facility (EHF) injector RFQ's are under study. R.F. stabilization techniques are actively being developed.

The HERA RFQ[7] is a 750 keV machine with a 60 mA current limit operating at 202 MHz. It is a low duty factor four vane structure with end cell resonant loop couplers to suppress the dipole modes. It is not yet resolved whether to include vane coupling rings; the structure length is about 3/4 of a free space wavelength reducing the sensitivity to tuning errors. The vanes will be industrially fabricated by Balzer. Cold models at 200 and 400 MHz were constructed to study this machine.

The EHF facility[8], proposed to go into the old ISR tunnel at CERN, consists of a 30 GeV proton ring and stretcher fed by a 9 GeV rapid cycling booster injected by a 1.2 GeV 1.2 GHz side coupled linac. The front end is a 50 MHz RFQ followed by a 400 MHz RFQ and a 400 MHz DTL. The 50 MHz RFQ is required to give the proper beam micropulse structure to boxcar stack the rapid cycling booster. The 50 MHz RFQ accelerates a 20 mA beam from 50 to 200 keV over a length of 2.2 meters, with the 400 MHz RFQ accelerating up to 2.5 MeV. A buncher cavity may couple the two RFQ's. The mechanical design of the RFQ's is not yet available.

The IAP group is also developing a split coaxial resonator[9], similar to Müller's at GSI, but with a four rod configuration. A 50 MHz 70 cm long machine has been built that has accelerated protons and H_2^+ to 50 keV/amu to near the space charge limit of 4 mA. A device 38 cm long with unmodulated rods has been built for use as a transport experiment. Later, a 49 MHz SCR RFQ to accelerate H_2^+ from 12.3 to 93.4 keV will be built that is 50 cm long.

The four rod structures developed at IAP consist of a simplified geometry in which the cell profile is essentially trapezoidal instead of describing the normal two term potential shape. They find that the field configuration on axis with this simplified electrode shape which can be easily manufactured on a lathe to have sufficiently low unwanted multipole amplitudes to be an effective accelerator.

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CERN

CERN presently has two operating RFQ's: the RFQ1 proton injector and the oxygen injector, both injecting Linac I. The beam dynamics design and vane fabrication of RFQ1 were done at LANL with CERN assembling the vanes in a coaxial manifold driven cavity of their own design. The oxygen RFQ was designed and fabricated at LBL and then moved to GSI for successful beam tests. This RFQ is now installed at CERN and has already produced oxygen beams to the end of the linac at 12.5 MeV/amu. A switching magnet selects one of the two injector RFQ's.

Two more RFQ projects are starting at CERN: an antiproton decelerator at LEAR[10], and an RFQ produced calibration beam on the L3 detector at LEP. The LEAR antiproton decelerator will take a 2 MeV beam bunched at 200 MHz in the ring down to an energy of 100 keV where an additional single cavity will adjust the energy in the 20 to 180 keV energy range with the phase spread out of the RFQ of only ±9°. The energy spread of the beam can then be further reduced from ±4 keV by a double harmonic debuncher. In one proposed experiment, the antiproton beam will be slowed down in pulsed electron traps to thermal velocity and the gravitational acceleration will be measured.

The LEP L3 detector, an electromagnetic calorimeter, contains 12000 BGO crystals as an electron and photon detector whose gain which will drift must be known to better than 1%. An RFQ[11], supplies a 1-1.5 MeV H^- beam, neutralized at the exit, which drifts through the 0.5T solenoidal detector field and strikes a lithium target near the center providing 17.6 MeV photons for detector calibration. The proton beam is provided by an H^- RFQ at low duty factor in continuous operation during experimental runs. Various designs of this relatively conventional RFQ are being evaluated by the Cal Tech team responsible for the calibration of the BGO detector.

An RFQ will eventually be installed on Linac II, but this program has been delayed. The RFQ will be built at CERN and may use external loops on the endwalls to control the dipole mixing.

Institute for Nuclear Studies, University of Tokyo

INS has completed two RFQ's, LITL, a $q/A = 1/7$ 100 MHz test machine, and TALL, a similar heavy ion machine with an output energy of 800 keV/amu 7.25 meters long requiring 180 kW. TALL[12] will be part of the injector chain for TARN-II, a small heavy ion synchrotron/cooler. The RFQ has no vane coupling rings and one drive loop. Each vane consists of four longitudinal segments with small separating gaps. The field uniformity is ±2% azimuthally and ±5% longitudinally. The LITL machine, 1.38 m long, has been driven cw to full gradient for periods of a few minutes. At 1/3 rated power, the frequency shift of 250 kHz is larger than expected and is probably due to a temperature rise of the vane tip of 30° C. INS has collaborated closely with industry, with major components for TALL fabricated by Sumitomo Heavy Industries.

Also at INS a quarter scale split coaxial RFQ is being developed to prototype a uranium ion accelerator. The 37.1 MHz machine is 2.1 meters long and has unmodulated vanes. These will be replaced with modulated vanes for a proton test. This machine is being developed in conjunction with GSI.

LBL

LBL has produced a silicon injector RFQ for the Bevatron and an oxygen RFQ for CERN. These 200 MHz heavy ion RFQ's pioneered the use of the vane coupling rings which stabilize the structure and simplify the tuning.

The LBL group has designed a 750 keV proton injector RFQ under contract to BNL and FNAL[13]. BNL expects to commission the fabrication of one unit to be used to replace one of the Cockcroft-Walton preinjectors of the 200 MeV AGS injector. This 200 MHz RFQ is of the same mechanical design as the two heavy ion machines and uses a new beam dynamics design based on the work of Wangler for the LANL BEAR RFQ. Here, the shaper is extended and the gentle buncher is reduced in length for a stable phase at the end of the gentle buncher of −50° ramping to −40° at the end of the accelerator. The large bucket and low injection energy of 35 keV provides a current limit of 110 mA and an output energy spread of ±14 keV at 50 mA. At an expected Q of 57% of the theoretical value, the cavity power is 100 kW.

In a separate effort at LBL Cooper and Anderson[14] have developed a sheet beam d.c. accelerator which uses the focusing inherent in electrostatic deflectors. They have generalized this device to a two dimensional r.f. linac. This device may have applications in accelerating a ribbon beam of large dimensions and current to high voltages.

Chalk River

CRNL has two programs underway: the cw four vane 270 MHz proton RFQ1 program, and a four rod 108 MHz sparker. The RFQ1[15], originally the injector for the now discontinued Zebra project, is now in a joint CRNL-LANL program to develop cw RFQ experience over the next year. This is a 1.5 meter long machine with OFHC copper vane tips and copper plated carbon steel vanes and cavity that runs at 1.5-2 kilpatrick with a loop driven cavity to produce 600 keV protons. The RFQ is expected to be tuned by winter '86, with first beam by late '87.

The four rod sparker[16] will use 1 meter long rods in a 1.5 meter long tank operating at 108 MHz cw. The rods are unmodulated. The high power tests will begin in the summer of '86. This is a joint program among CRNL, LANL and the University of Frankfurt (IAP).

TRIUMF

A preliminary study has been made at TRIUMF with assistance from CRNL for a $q/A > 1/60$ RFQ to accelerate singly charged heavy ions produced in a hot reaction target at the ISOL facility at TRIUMF[17]. The four rod RFQ structure accelerates a 1 keV/amu beam to 60 keV/amu at 23 MHz over a length of 9.2 meters. The beam dynamics design of this RFQ is unusual in that the vane (rod) voltage rises from 38 kV at the entrance to 97 kV at the exit. As the ion gains energy, the gap defocusing term decreases, needing less focusing, so that the aperture may be increased allowing the vane voltage and the rate of energy gain to increase.

At an exit energy of 60 keV/amu the beam is stripped to $q/A > 1/20$ in a gas cell and further accelerated to 1 MeV/amu in a 23 MHz Wideröe type structure similar to the Riken, GSI and LBL structures. The research funding for this project this fiscal year has been postponed.

KEK

KEK is constructing an RFQ[18] that will replace the Cockcroft-Walton set on either the H^- or the polarized proton source. It is not yet decided which will be replaced. The 201 MHz 750 keV RFQ is injected at 50 keV and has a vane length of 136.4 cm. The cavity has a rectangular cross section using electron beam welding (EBW) of the vanes to the side plates and EBW of the flexible diaphragms joining the side plates.

After the first tests, two sets of vane coupling rings were added to widen the quadrupole-dipole mode separation from 1.5 to 6.3 MHz, dropping the quadrupole frequency 3 MHz which was made up for by EB welding tuning bars to the sides of the vanes. The structure has run to full gradient and beam tests are expected to start in May '86.

AccSys Technology, Inc.

This young startup company in northern California will be supplying RFQ's to industry[19]. They have developed an RFQ of conventional design for use in hospitals to produce short lived radionuclides. They will supply an ion source, RFQ and LEBT as a complete package.

AccSys has also developed a sparker to test NPB applications of cavity design and vane tip material. The 490 MHz sparker cavity is 50 cm long with unmodulated vanes and no vane coupling rings. After one hour of initial tuning the dipole component was 2% of the quadrupole amplitude. The sparker is space qualified and is designed to withstand a shaking test without detuning and will be tested soon to high field in an external vacuum can.

Other Laboratories

GSI continues work on the Maxilac, a 12 MHz SCR structure accelerating U^{+2}. At the present, the structure is completed to the 45 keV/amu point and working well.

BNL and FNAL have contracted a study at LBL[13] for the design of a 750 keV proton RFQ as a Cockcroft-Walton replacement. BNL expects to commission the fabrication of an RFQ by LBL to be delivered in 18 months.

The Texas Accelerator Center (TAC) is designing a 2 MeV proton RFQ to test vane tip materials and modulation shapes[20]. The plan is to fabricate the RFQ from nonmagnetic stainless steel, and copper plate the cavity except for the vane tips, which should hold off a larger voltage than copper. They are also considering a more extreme vane tip profile to increase the accelerating gradient. Some construction work will begin immediately with a target date for completion in early '87.

The Institute of Chemical Research at Kyoto University has started construction on a 7 MeV proton linac injected by a 2 MeV RFQ. The developoment work has been perfomed in close contact with outside industry. The details of the system are budget driven at the present.

Odera then at Riken has proposed a chain-like linac structure that is basically an Alvarez linac but provides RFQ-like electrostatic focussing[21]. This structure maintains a higher shunt impedance in the energy range above the usualy RFQ energies.

Structure Stabilization

The RFQ requires a pure r.f. quadrupole potential on axis without any dipole admixture. Some structures, such as the four rod and the split coaxial structures and to a lesser extent the Soviet double H structure are immune from dipole interference. The popular four vane structure, however, does suffer from two degenerate dipole modes mixing with the quadrupole mode. The RFQ is comprised of four weakly coupled waveguides at cutoff with the quadrupole field the algebraic sum of the fields in the four quadrants. The longitudinal variation of the field in each quadrant is proportional to the square of the length normalized to the free space wavelength times the local variations in the vane tip capacitance. Therefore long RFQ's are very susceptible to azimuthal asymmetry and longitudinal field variations.

If the opposing vane tips are connected together with vane coupling rings (VCR's), which effectively push the dipole mode to a higher frequency than the quadrupole mode, the azimuthal symmetry for quadrupole excitation is strongly improved, and the tuning procedure is simplified to establishing a flat longitudinal field[22]. This can usually be done by adjusting the position of the endwalls. The VCR's lower the frequency of the RFQ, however, and the locally lower resonant frequency in the vicinity of the VCR's causes a bump in the longitudinal field. If this is taken into account in the design of the accelerator, it causes no problem.

Several other schemes have been invented which separate the dipole modes from the quadrupole mode without the disadvantages of the VCR's. Pirkl[23] has inserted loops into the end region which interact with any dipole component. He has also proposed external coaxial cables penetrating the endwall and connecting to the vanes themselves. Schempp has proposed loops traversing the vanes coupling quadrants, as well as circuits external to the RFQ connecting adjacent quadrants. Schempp[24] has also proposed external resonant lines periodically penetrating each quadrant for longitudinal stabilization.

Potter originally proposed the coaxial manifold as used on the AT-2, FMIT and Saclay machine. The coupling from the manifold to the four quadrants is weak, and offers no stabilization. Resonant coupling from the manifold to the RFQ would increase structure stability but a high power solution is elusive. Potter has also developed an interesting TEM coupler for longitudinal stabilization to be used in conjunction with vane coupling rings for azimuthal stabilization. This consists of a conductor along the center of a quadrant connecting opposing vanes at particular locations.

Beam Dynamics Design

The complete freedom to specify any form of the longitudinal field along the length of the RFQ without significantly perturbing the transverse focusing strength has resulted in RFQ designs with nearly 100% capture and small longitudinal emittance. In the design process, three independent parameters are specified, usually B, ϕ_s and A (see Wangler[6] for notation) along the structure. The design process usually requires that the acceptance and space charge limit be maximized and the power, length and emittance growth be minimized with many additional constraints being simultaneously satisfied, the most demanding being the peak surface field limitation due to sparking and the minimum longitudinal radius of curvature of the vane tip which sets the cutter size.

The method developed by LANL[4] to divide the RFQ into four sections (radial matcher, shaper, gentle buncher and accelerator) has been almost universally adopted, particularly because LANL has provided design codes to other laboratories. In the gentle buncher the beam is adiabatically bunched, usually holding the bunch length constant which optimizes the longitudinal space charge limit, while simultaneously adjusting the transverse focusing strength so the transverse and longitudinal space charge limits are equal at the end of the gentle buncher. If the gentle buncher started at an input stable phase of -90° the adiabatic approximation would produce an infinitely long bunching section, so the shaper provides a short linear variation of ϕ_s and A to get the buncher started. A radial matcher at the beginning converts a round time independent beam to a beam whose transverse cross section matches the phase of the uniform transverse focussing in the structure, and the final accelerator section takes the beam to full energy, usually with constant values of a and m. Inagaki[25] showed in 1980 that even a linear ramp of ϕ_s and E_z can capture nearly 100% of the beam.

At LBL the design of the silicon injector RFQ where space charge is not an issue but length is because of the low q/A, Yamada[26] modified the LANL design by introducing a prebuncher section in front of the buncher to ramp the longitudinal field on faster, and a booster section after the buncher to again ramp up faster, shortening the accelerator at the expense of reducing the bunch length. The oxygen machine designed and built at LBL for CERN used the same design approach.

The LANL design method calls for a short shaper section and then ramping the stable phase to its final value, usually -30° in the buncher section. A recent improvement, due to Wangler[6], and first demonstrated in the design of the BEAR machine resulted in an improved space charge limit with a lower power requirement. This was obtained by lengthening the linear shaper and reducing the length of the gentle buncher, with a stable phase at the end of the buncher of -45°. The larger bucket and longer bunch reduces the charge density, increasing the space charge limit. In turn, the injection energy can then be lowered, shortening the phase oscillation wavelength, and thereby shortening the machine while keeping the number of phase oscillations constant. The shorter machine requires less power. In the BEAR design, the value of B in the accelerator section was not constant, causing the local resonant frequency to vary, potentially causing variations in the vane voltage along the RFQ.

This design was further developed at LBL[13] by using even a larger bucket in the buncher and then ramping the values of A and ϕ_s in the accelerator to keep B and the local resonant frequency constant. It was found that the energy spread of the beam at the exit of the RFQ was as much as a factor of four below that of the conventional design, as well as requiring about 60% of the power and a lower injection energy compared to a conventional design. This design is used in the RFQ that LBL is supplying BNL as a Cockcroft-Walton replacement.

The Saclay heavy ion RFQ[27] uses a different approach to reducing the energy spread at the exit. As the beam approaches its final energy of 183 keV/amu, the acceleration field is ramped to zero to produce a drift section with focussing only. Near the end of the RFQ a non-accelerating bunch rotator section reduces the momentum spread. Due to the large phase spread at the exit, a six cell radial matching section must be included to match the beam to the following transport system.

LBL has developed a scenario of using a heavy ion RFQ as a transport channel for a high energy proton beam. The present Bevatron injector uses a 200 keV/amu silicon RFQ injecting two tandem Alvarez tanks operating in the $2\beta\lambda$ mode accelerating to 5 MeV/amu. If an 800 keV proton RFQ is injected directly into the linac operating in the $\beta\lambda$ mode, a 20 MeV beam will be available for the Bevatron. Since the heavy ion RFQ is closely coupled to the first Alvarez, the only way to get the proton beam to the DTL is by drifting it through the heavy ion RFQ.

Beam simulations show that if the drift through beam is not synchronous with the spatial accelerating harmonic in an RFQ that its energy spread is negligibly affected at r.f. amplitudes sufficient for efficient transport. There is no program at LBL to pursue this option in the near future.

RF Modeling Codes

The code PARMTEQ, developed at LANL as an descendent of the DTL code PARMILA, remains the standard. There are several variants of this code which differ in the choice of the independent variable of integration through the cell and the treatment of the space charge forces. Since this code only integrates the particles through the cells and does not do any design itself, and is used at all laboratories developing RFQ's, it is the standard by which various design methods can be compared.

LANL has developed an RFQ design code, RFQUIK, that applies the principles of the adiabatic capture section to generate the basic parameters of an RFQ. The associated CURLI code analyzes the space charge response. Other laboratories have developed similar front end codes such as GENRFQ at LBL specializing in heavy ion RFQ's and a code at Saclay for full cell-by-cell optimization of parameters. Wadlinger and Lysenko at LANL have written global RFQ design optimization codes. These codes search specified parameters in an attempt to reach an optimized constrained solution.

The detailed multipole fields at the vane tips in three dimensional geometry have been determined by Crandall[28], Diserens[29], Junior[30] and others. Self-consistent particle simulation codes that solve the pole tip geometry electrostatics problem in three dimensions with the beam space charge included have been produced by Drobot, Whealton[31], Spädtke[32] and others.

Emittance Growth

A number of numerical studies of emittance growth in the RFQ have been made over the years. The effects studied have included mismatch, steering errors, resonances and envelope instabilities. Haber[33] has used FFT techniques to increase the number of particles in simulations to tens of thousands.

An agreed-upon basis for the establishment of the space charge limit in an RFQ is an arbitrary one: the space charge limit is defined as the current that depresses the transverse tune to 40% of its zero current value. Most simulation experiments which use the SCHEFF space charge code in PARMTEQ indicate that at half this space charge limit the emittance blowup is usually negligible and the saturated linac transmits a current of on the order of this space charge limit.

The SCHEFF space charge routine fits the bunch into a set of concentric rings sliced longitudinally, removing asymmetries and details of the charge distribution. More elaborate codes by Diserens[34] and Kuo, for example, which include the image currents on the vane tips and asymmetries in the beam usually predict a larger loss of the beam.

More recently, Wangler[35] et al. have developed a model for emittance blowup in continuous or periodic focusing channels from a suggestion of Gluckstern. In this model, the nonlinear component of the space charge due to the particular charge distribution produces a self-electric field energy due to this nonuniform charge distribution. This field energy relaxes and is exchanged for rms transverse emittance. Particle simulations show that this model accurately predicts analytically emittance growth for various initial charge distributions.

Wangler has recently modified this model for bunched beams by proposing that the emittances in the three planes equipartition. Therefore, the nonlinearity of the bunch causes emittance increase in the three phase planes, and equipartitioning exchanges energy between the planes in a predictable way. These models may lead to a more fundamental understanding of emittance growth.

Vane Tip Field Multipoles

The first group of RFQ's built used a vane profile given by the two term potential function. The hyperbolic transverse cross section is approximated by a circular cross section and the surface field enhancement at the closest approach of the vane tips is 1.38 times that of two parallel planes of the same spacing. In the presence of modulations, the field enhancement can be as much as 10% higher than this, which may induce sparkdown. Analyses by Crandall and Diserens using 3-D electrostatics codes with the two term pole tip shape and others, particularly a constant transverse radius of curvature shape, showed that the field enhancement could be reduced to 1.25 for a radius of curvature $0.75r_0$. The higher multipole harmonics were more significant, but simulation codes showed that in most cases they were not damaging. The A_{10} spatial harmonic that is synchronous with the ion velocity of all these various geometries is less than the two term potential acceleration parameter A, averaging about 93% for the variable r_0 geometry, and must be compensated for in the machining of the modulations.

The modulations are cut into the vanetips by a ball end mill in most cases. The choice of RFQ parameters influences the minimum longitudinal radius of curvature of the modulations, dictating the size of the ball mill cutter. In practice, the selection of the cutter size is a significant constraint on the RFQ parameters. Tests have been carried out at LANL with a flying cutter with appropriate cross sectional profile to produce the modulations, speeding up the vane production process. The author is not aware of any operating RFQ's that have been produced in this way.

At IAP, Frankfurt, the four rod structures are using a vane tip profile that differs considerably from the two term potential geometry[30]. The modulation profile at the surface of the rod may be trapezoidal or even more extreme. Calculations at IAP show small higher multipole amplitudes on axis.

Chidley and Diserens[36] have analyzed the effect of the higher order multipoles on large bore high current RFQ's. Using the CHARG3D code to predict the potential from several vane tip profiles, they find that the transmission of a high current beam in an RFQ1 sparker example to be poor for the LANL POP vane tip profile, improving slightly for a constant radius of curvature geometry, and somewhat improved for a geometry that uses a constant center of curvature with the tip center $1.75r_0$ from the beam axis.

Surface Field Limit and High Duty Factor Operation

The space charge limit and transverse acceptance of an RFQ increase rapidly with the peak surface field assumed in the design. Expressed in units of kilpatrick (1 kilp = 14.7 MV/m at 200 MHz, 19.8 MV/m at 425 MHz) short pulse RFQ's operate up to 2 kilpatrick and long pulse and cw RFQ's somewhat less: 1.68 kilp for the FMIT RFQ. Tests of surface sparking show a rate proportional to duty factor to pulse lengths of about 10 milliseconds, and then flattening out. Very short pulse RFQ's may be therefore pushed to relatively high surface fields.

Sparker experiments have been carried out at a number of laboratories. The results tend to show that pushing short unmodulated vane sparkers to 3 kilpatrick is possible for short pulses, even for aluminum vane tips. No full scale RFQ has yet been designed for a field of over 2 kilpatrick.

The material near the vane tip will be sputtered away during operation. Tests at LBL showed that thin copper plating over a mild steel substrate will disappear in a matter of hours of cw operation at a low frequency of 60 Hz[37]. In an RFQ, sputtering of the vane tips would produce a change in resonant frequency of the machine, which has not yet been observed in any operating RFQ.

Cryogenic (as opposed to superconducting) operation of ion linacs is an option to reduce the cavity power. Copper structures at 20°K have an r.f. surface resistance 10-15% of that at room temperature. Many problems need to be solved, but tests have taken place at LANL for a single cell cavity. Experiments by Tanabe at Varian[38] in a small cryogenic electron cavity at fields much higher than those used in ion linacs showed an anomolous increase in r.f. resistivity at high magnetic fields that is not yet understood. Cryogenic cavities are of interest to the U.S. Army as reflected in a recent basic research program announcement.

Funneling and Multiple Beams

Funneling combines two beams of frequency f with bunches alternating in time to a single beam of frequency $2f$. As the space charge limit of an accelerator system is imposed at the low energy end, a tree of linacs can be formed with the beginning cells of each funneled section operating near the space charge limit. Many such scenarios were studied for linac loaded synchrotron inertial fusion drivers.

The difficulties of funneling were not completely appreciated until Bongardt[39] studied in detail the emittance blowup mechanisms of funneling two RFQ's for the SNQ spallation source driver with a conventional r.f. transverse deflector and careful design of the beam transport system. He found that the nonlinear tune depression due to space charge was responsible for a redistribution of the beam and in addition, the sinusoidal variation of the deflecting field caused some emittance increase in the plane of the deflection. The outcome was that the total current was doubled by summing the two RFQ's, but the brightness was in fact decreased by the emittance blowup.

An alternative funneling geometry has been developed by Stokes[40], but not yet analyzed for its effect on the beam parameters. It operates on the principle that an offset quadrupole will deflect the beam. An RFQ focusing channel is provided with a periodic offset that will deflect a beam depending on its r.f. phase. This satisfies the criterion of funneling and adds the property of continuous transverse focusing. The focusing may reduce the emittance blowup that Bongardt found, and the addition of a bunching voltage may reduce the emittance growth caused by a sinusoidal deflecting force by reducing the bunch length. A practical form of this funnel has not yet been proposed.

Technology Transfer to Industry

The federally funded national laboratories represent a large investment in resources. The Congress has found that many new discoveries and advances in science occur in universities and federal laboratories and that application of this knowledge depends largely on actions by business and labor. To strengthen cooperation among these institutuions, Congress has passed the Stevenson-Wydler Technology Innovation Act of 1980 that mandates that each federally funded laboratory whose budget exceeds $20 million to make available no less than 0.5% of that budget to support technology transfer to industry.

Multipurpose laboratories such as LBL have no trouble in meeting this requirement. Single purpose laboratories such as FNAL satisfy this requirement, for example, by working with outside agencies in the area of the design and fabrication of particle accelerators for biomedical applications and in the transfer of cryogenic technology. At LBL the technology transfer activities are handled through the Office of Research and Technology Applications (ORTA).

The same 96th congress that passed the Stevenson-Wydler act also passed the Dole-Bayh act that mandates that the national laboratories should license patents to industry more aggressively. Previously handled through Washington, the laboratories can elect to file and license a patent directly. In addition, the inventor is now able to receive royalties for an invention licensed to the laboratory.

Small business activities, such as AccSys Technology, Inc. are springing up, staffed by those with strong connections to the national laboratories to produce RFQ's as a commercial venture. The national laboratories are not allowed to compete with private industry. We will see the maturing RFQ technology, developed in the federally funded laboratories, move to commercial industry. Already RFQ's have been industrially fabricated for LANL, IAP, LBL and others.

Summary

In just a few short years from the Russian invention and demonstration of the POP machine at LANL, RFQ's have matured to the point where many varieties have been developed and are successfully operating on a daily basis. New beam dynamics and mechanical designs will result in improved beam performance in smaller and lower power machines. RFQ's are now starting to move to the marketplace in areas such as biomedical research and materials detection and testing. In analogy with the development of small commercial electron linacs, the RFQ allows the acceleration to MeV energies of protons and light ions in a compact and economical package. This will open up a whole new spectrum of applications.

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