ADVANCED ULTRAFINE PARTICLE ACCELERATOR

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Abstract: The conceptual design of an Ultrafine Particle Radio Frequency Quadrupole (UFP-RFQ) accelerator is discussed. The results indicate that it is possible to accelerate 1 μm radius Al particles to velocities around 100 km/s in 100 m RFQ length. This accelerator can provide variable output particle velocity, with capability of handling different particle materials with different sizes. There are scientific, industrial and space applications in the collisions of such particles with targets.

1. INTRODUCTION

Recent results show that the Los Alamos National Laboratory (LANL) 6 MeV Van de Graaff is capable of accelerating particles up to 30 km/s [1]. The particles' masses are small ($\sim 10^{-14}$g), so that the diagnostics are quite challenging. For larger particles ($\sim 10^{-11}$g), the velocity is lower (~10-15 km/s), so that the physics of higher velocity impacts cannot be explored with particles in the picogram mass regime. The increase in particle mass and speed available with a RFQ accelerator makes possible the use of wider range of powerful diagnostic techniques to address a greater variety of interests in the applied and basic scientific community. It also aids in overcoming some of the ambiguities in experimentation due to microstructural effects, when the impacting particle is so small that it interacts with a single grain in a metal, or one portion of a composite, heterogeneous target.

LANL has sponsored the preliminary design of such an advanced accelerator. Section 2 describes the RFQ structure which is followed by the conceptual design of the RFQ in Section 3. The results are described in Section 4. The RFQ operational flexibility it discussed in Section 5. There are several physical processes by which a charged micro-particle may lose its charge during acceleration. These are discussed in Section 6.

2. RFQ STRUCTURE

The most conventional RFQ structure consists of a four-vane cavity in a cylindrical geometry. This RFQ is typically used to accelerate light ions to a few MeV. Rf acceleration techniques have never been applied to the acceleration of charged microparticles. Here particles are millions of times heavier per unit electrical charge than protons. Consequently, rf accelerators to accommodate them must be very different from their proton and heavy-ion counterparts - so different, in fact, as to require a totally different electrical and mechanical structure.

The resonant frequencies of the RFQ structures, for charged microparticles, are in the 200-400 kHz range, or approximately 1000 times lower than that of the usual proton RFQ's. This fact alone necessitates an entirely different resonant and mechanical structure. The first of the new structures is a four-bar structure, for producing the focusing and accelerating fields that act on the particles, connected to an external multiturn inductor to produce the extremely low resonant frequency. The second structure is a succession of four-finger electrodes of alternating polarity, for producing the fields that act on the particles, connected to an external multiturn inductor for similar reasons. The former is preferred at the lowest velocities and the latter is preferred beyond some critical velocity. The two structures are shown in Figures 1 and 2.

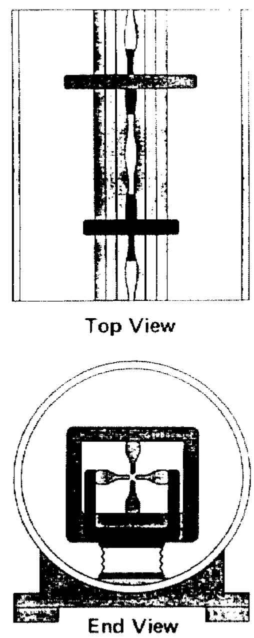

Figure 1 Four-Bar RFQ Linac Structure

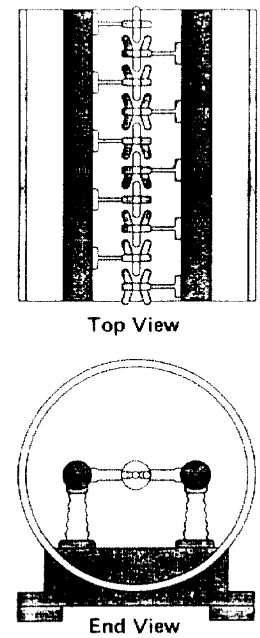

Figure 2 Four-Finger RFQ Linac Structure

3. CONCEPTUAL DESIGN

The analysis of the performance of RFQ structures starts with the utilization of the RFQ design tool, RFQSCOPE, and progresses through the utilization of the well-tested beam dynamics code, PARMTEQ. It is important to ascertain the practical values of input parameters to RFQSCOPE to achieve a reasonably good estimate of the code outputs, e.g., RFQ length. The radio frequency was selected to be 0.2 MHz. The other major input parameters are: (1) Microparticle surface field (E_s), (2) Particle injection energy to the RFQ, (3) Particle source emittance and (4) Peak electrode surface field.

Friichtenicht and Becker [2] experimentally obtained the maximum surface field for various sub-micron particles. The values obtained for iron (r = 0.022 μm) and aluminum particles (r = 0.034 μm) are 10×10^9 and 3.3×10^9 V/m respectively. There are presently theoretical and experimental investigations to find the maximum surface field of larger microparticles [3]. For the purpose of the preliminary design of the RFQ, a constant surface field of 5×10^9 V/m for various materials with different diameters has been assumed.

It has been shown that a 200 keV extraction voltage from the microparticle source is quite feasible and this has been chosen for the injection energy of the particles into the RFQ. The present LANL source has an un-normalized emittance of about 2.5×10^{-4} cm-rad. This value was adopted for the RFQ design. The peak voltage between the electrodes in the RFQ is limited by the voltage breakdown, which itself is dependent on a number of variables including background gas pressure, electrode shape and electrode surface quality. Depending on these variables, a range of values from 20 MV/m to 40 MV/m or more may be achieved. It is planned to measure the voltage breakdown for various electrode shapes and materials. The RFQ length increases by ~1/3 if the surface field decreases from 30 MV/m to 20 MV/m and decreases by 25% if the surface field increases from 30 MV/m to 40 MV/m. A surface field of 30 MV/m was assumed for the design.

4. RESULTS

As the particle velocity increases, the acceleration efficiency of the RFQ structure decreases. Going to higher frequencies would help to increase the acceleration efficiency, but would decrease the focusing strength to an unacceptably low value. The four-finger structure allows one to go to higher frequency to improve the acceleration rate and to maintain a longer focal periodicity required to preserve the focusing strength.

A five-section RFQ that starts with a four-bar section at 220 kHz, followed by four four-finger sections at successively higher frequencies, accelerates microparticles from 200 keV/proton charge to 100 MeV/proton charge in a length of 100 m. The parameters of this configuration are presented in Table 1. The first section accelerates 1 μm radius Al particles to 40 km/s in a length of 20m. The beam trajectories are stable. The capture efficiency is about 94%. The particle energy fluctuation at the end of this section is only ± 0.2 Mev which is 1.3% of the final particle energy. The velocity spread is, therefore, less than 1.2%. The average power requirement of the total RFQ is about 82 kw. The five-section RFQ has a capture efficiency of ~60% for a single particle. This efficiency drops to ~30% for a ±15% variation in M/Q. M and Q are the particle mass and charge respectively. The Low Energy Beam Transport (LEBT) system takes the particles from the source and focuses them into the RFQ. The LEBT length in 80 cm and the focusing elements are three electro-static quadrupole lenses in a conventional triplet configuration.

(M/Q = 2000000)

Section	Freq (MHz)	Final Energy (MeV)	Final Velocity (km/s)	Final Length (m)
1	.220	16.3	40.0	20
2	.440	36.7	60.0	40
3	.660	59.4	76.0	60
4	.880	84.0	90.0	80
5	1.100	110.6	103.0	100

Table 1 Five Section UFP-RFQ

5. RFQ FLEXIBILITY

It is desirable to design an RFQ with not only variable output particle velocity but one that can handle different particle materials and sizes. The multi-section RFQ can provide several discrete velocities, corresponding to the output velocities of each section. The output velocity of any section can be transported through the remainder of the RFQ without acceleration, by simply decreasing the excitations of the latter sections of the RFQ. Those sections will not accelerate the beam, but will provide the necessary radial focusing to keep the beam from expanding and hitting the RFQ electrodes.

A continuously variable output velocity is feasible by designing a variable-frequency multi--section RFQ. In this design, the output velocity of each section is proportional to the frequency. The extent of frequency variation depends on the practical design considerations of the external inductor needed to resonate the RFQ capacitance.

Figure 3 shows the parameter space and the operational flexibility of a five section RFQ designed to accelerate 2 μm diameter aluminum projectiles to a velocity of 100 km/s. All velocity and M/Q combinations in the shaded regions can be produced by this multi-section RFQ. For example, if we move towards the right of point A on the hyperbola, we cold accelerate heavier particles by decreasing the frequency. Assuming that the upper limit of frequency is twice the design point frequency, the M/Q could be increased by a factor of 4. This results in a particle mass increase of a factor of 64. The corresponding velocity would be around 50 km/s. Now if we move left of point A on the hyperbola, we could accelerate lighter particles by increasing the frequency. The M/Q could be decreased by a factor of 4, assuming a lower limit of frequency equal to half the frequency of the design point. This also results in the particle mass reduction by a factor of 64. The corresponding velocity would be around 200 km/s. Therefore, this RFQ is capable of accelerating particles with ratios of heaviest to lightest particles of about 4000. For a specific particle, this translates into a diameter ratio of 16.

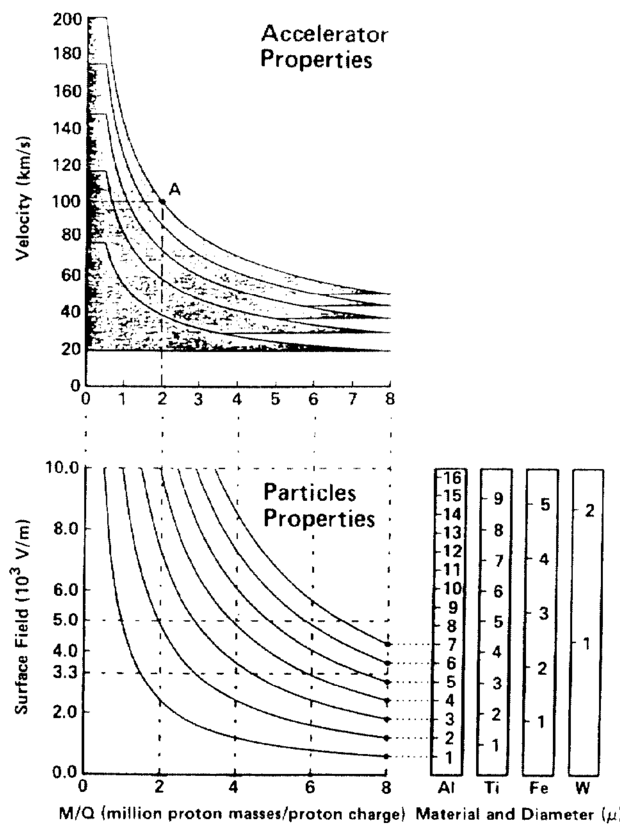

Figure 3 Ultrafine Particle RFQ Parameter Space

Now if we move towards left of point A on a horizontal line, lower masses can be accelerated without changing the frequency and without increasing the velocity. This could be accomplished by simply decreasing the excitation of all the sections as depicted in Figure 4. For example, moving from A to B, we must lower the excitation of all the sections to 50% to accelerate a particle with M/Q ~ 1×10^6 to 100 km/s. Moving down from point A on a vertical line, lower velocities could be obtained for the same M/Q by reducing the frequency and the excitation level of all the sections.

Therefore, it could be concluded that although the RFQ has been designed for M/Q = 2×10^6 and v = 100km/s, it can operate continuously over the following ranges:

$20 \leq v \leq 200$ km/s

$0.5 \times 10^6 \leq M/Q \leq 8 \times 10^6$

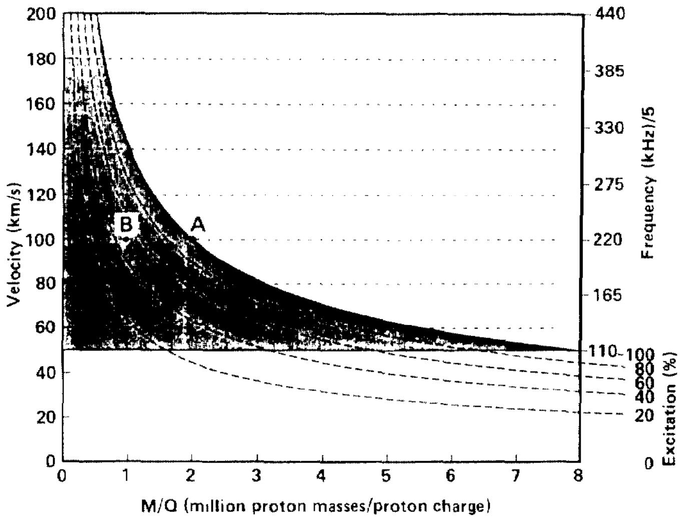

Figure 4 Ultrafine Particle RFQ Flexibility (final section)

This is an impressive operating range which can be accomplished by radio frequency variation of $1/2f_o < f < 2f_o$ where f_o is the design point frequency. This operating range can increase even more if one can increase the voltage gradiant in the RFQ electrodes from 30 MV/m to 40 MV/m. The result is shown in Figure 5 where the M/Q upper limit increases from $8x10^6$ to $16x10^6$.

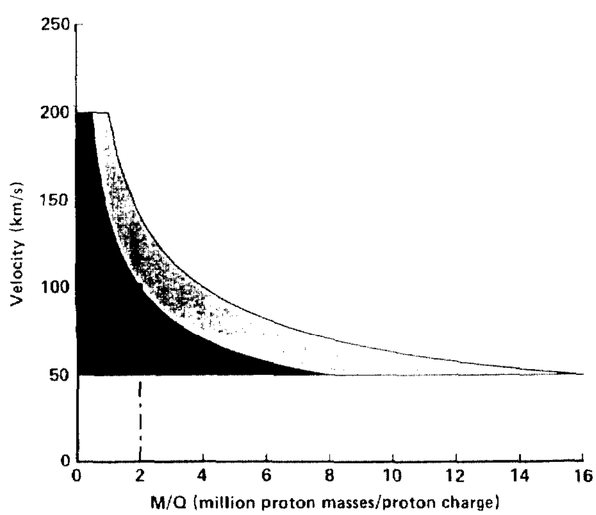

Figure 5 The Operating Range for 40 MV/m

6. INTERACTION OF MICROPARTICLE WITH BACKGROUND GAS

There are several physical processes by which a charged microparticle moving at tens of km/s interacts with the molecules of the background gas. The major interaction processes are elastic and inelastic collisions, sputtering and field effects. These interaction may result in microparticle velocity loss (drag) as well as electric charge loss. Due to the complexity of the problem, a quasi-quantitative approach was selected to access these processes. The result indicates: (1) drag forces are negligible under the condition of interest; (2) maximum temperature of the microparticle is substantially below the melting point of the particle, thus, ion evaporation is not an issue; (3) at surface electric fields of interest ($1x10^9$ - $1x10^{10}$ V/m), the probability of ionization is negligible and thus the field ionization will not contribute to charge loss from the microparticle; (4) the charge loss due to sputtering is negligible at $3x10^9$ V/m and increases with the field; (5) the charge loss due to impact ionization is a function of the ionization probability of impact particles and the probability of leaving the microparticle as ions. There is a wide range of estimates of these probabilities. These values were selected in such a manner to give the most conservative estimate of the background gas pressure level. For a particle traveling at 100 km/s over the last RFQ section, with $E_s = 3x10^9$ V/m, the background gas pressure should be about 10^{-7} Torr for 10% charge loss during acceleration.

7. CONCLUDING REMARKS

The advantage of these new RFQ linac structures over prior art (Van de Graaff acceleration) are shown clearly in Figure 6. In this figure, the performance of a 100-m-long, 100 MeV/proton charge RFQ Linac is compared to that of a 6 MeV Van de Graaff electrostatic accelerator. Comparison of points A and B shows that, for the same particle, the RFQ Linac offers 16 times the energy/particle and 4 times the velocity. Comparison of points B and C shows that for the same velocity, the RFQ Linac can accelerate 4096 times the mass resulting in 4096 times the energy/particle.

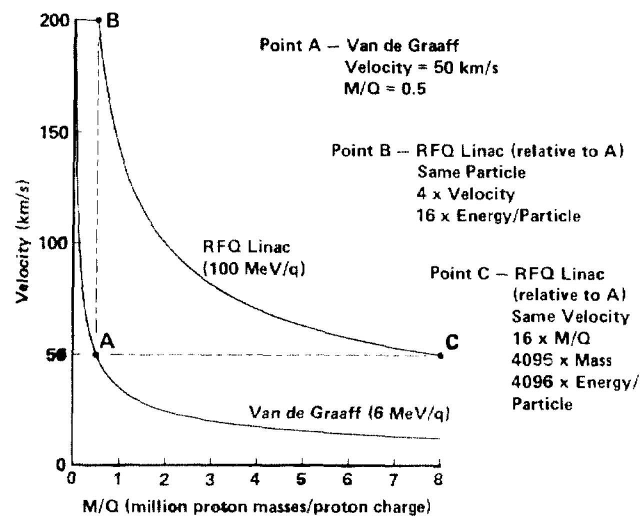

Figure 6 RFQ Linac/Van de Graaff Comparison

These new accelerating structures clearly open an entirely new range of laboratory-produced microparticle velocities, masses and energies.

The major applications that have been envisioned so far for the UFP-RFQ are: (1) impact phenomena study; (2) equation of state measurement; (3) validation of computer models; (4) validation of scaling laws; (5) micrometeriod physics; and (6) propulsion application.

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