High-performance RFQ Confinement of Radioactive Beams

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Introduction

Recently, RFQ confinement has become widely used to cool and collect weak radioactive ion beams, thereby greatly decreasing their phase space volumes and hence their emittances, both longitudinal and transverse. It is desirable to be able to apply this technique to more intense beams, such as those that are emitted by many ion sources of radioactive beams. This would allow high-resolution magnetic sector mass spectrometry on the beams so as to remove unwanted components. In many cases it would also allow the full beam to be captured in a trap if that is what is desired.

However, because of radially expansive space charge forces current systems are limited to beams of about 10 nA. Overcoming these space charge forces requires RF voltages and frequencies considerably above those currently employed. This presentation outlines what is believed to be a practical approach to the problem.

The Basics of RFQ beam cooling

The basic principle of RFQ beam cooling is to radially confine the beam while its particles are slowed and cooled in a bath of low-pressure helium. (Other gases may be used, the basic requirement being that the beam particle mass be considerably greater than the molecular mass of the gas. If, in fact, the molecular mass of the gas is greater than that of the confined particles the particles are not cooled but heated by their driven RF motion against the gas molecules[1,2].) The structure and electrical potentials used to confine the beam are shown schematically in fig. 1.

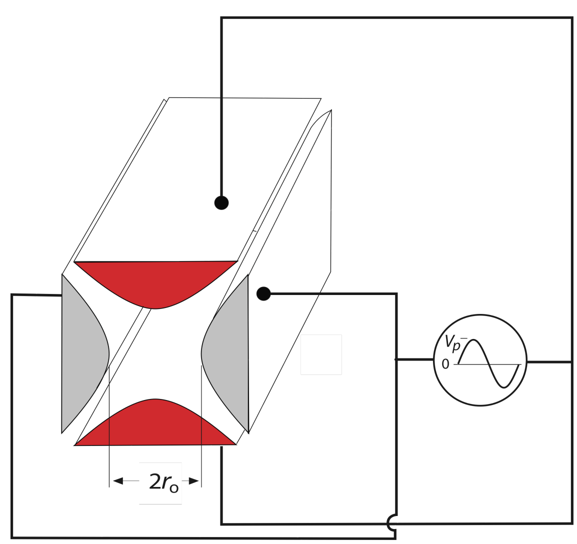

Fig. 1. A schematic of the RFQ structure and electrical potentials that provide the RFQ confinement for beam cooling and collecting.

A typical overall system that uses RFQ confinement for stopping, cooling and bunching an ion beam is shown in fig. 2.

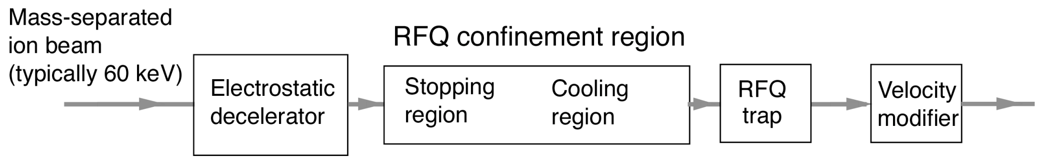

Fig. 2. A typical RFQ system for cooling and bunching an ion beam.

The ISOLTRAP facility at ISOLDE, CERN, was the first to implement such a system. The operational features of that system are shown in fig. 3.

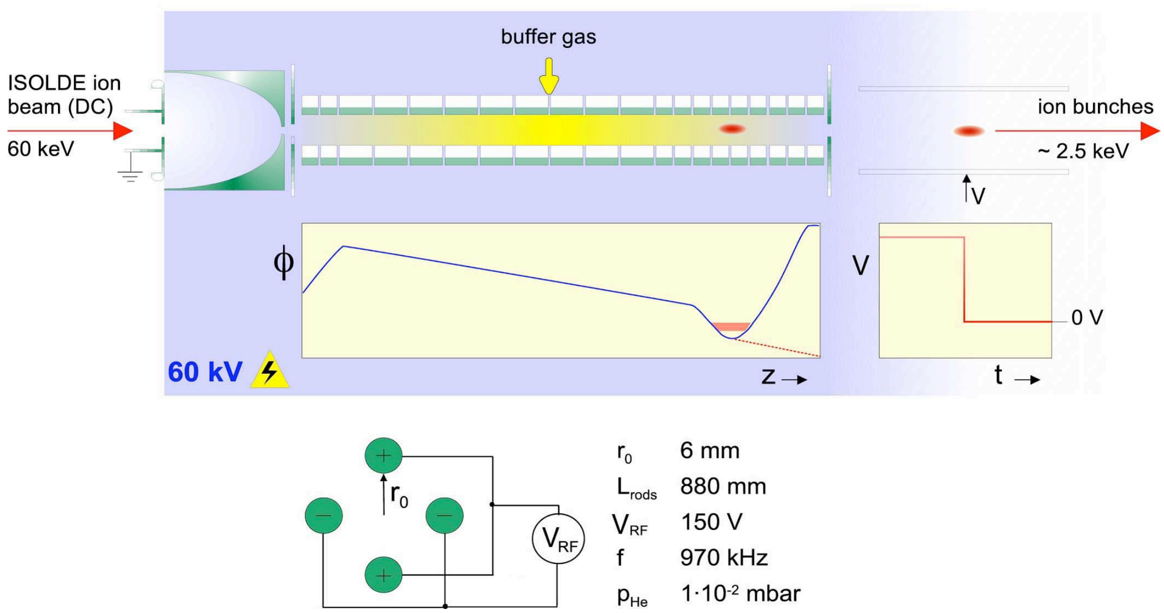

Fig. 3. A schematic of a typical RFQ beam cooler-buncher. The parabolic shaped electrode at the entrance to the system is a specially designed decelerator that slows the beam while focusing it onto the entrance into the RFQ structure. Within the structure there is a DC axial field gradient, achieved by axially segmenting the RFQ electrodes and applying different DC potentials to each quadrant segment. Initially there is a steep decelerating field that brings the incoming ions to rest within the RFQ structure. There is then a gentle dragging field to pull the stopped ions through the gas. At the far right of the structure the axial potential gradient forms a trap in which the ions are collected. At the desired instant this trap is emptied by applying an extraction field. Outside the trap the ion bunch enters a cavity that is pulsed toward ground while the ions are inside it. The setting of this lower potential determines the kinetic energy at which the ion bunch is delivered to the rest of the ISOLTRAP system.

The Action Diagrams of a Typical RFQ Beam Cooling System

The action diagram of ions under RFQ confinement is basically the right ellipse of the simple harmonic "macro" motion distorted by the driven RF motion (fig.4). At any instant this distortion retains the ellipticity of the action and its area, merely reorienting the semiaxes and changing their ratios.

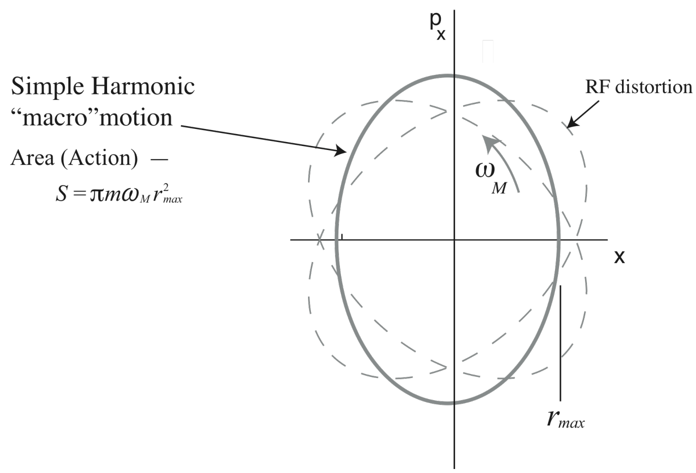

Fig. 4. The action diagram of particles under RFQ confinement. The action for the simple harmonic macromotion is shown as a solid-line right ellipse, the "x" semiaxis being simply the amplitude of the motion and the momentum semiaxis being this amplitude multiplied by the ion mass and the angular frequency of the macromotion. Representative cases of the distortion due to the driven RF motion are shown as dashed ellipses.

The action area is therefore determined by the dynamics of the macromotion. After many collisions with the cooling gas this motion will be come to thermal equilibrium. But, because of the prevailing driven RF motion this equilibrium will not be at the buffer gas temperature but elevated somewhat above it, a phenomenon commonly referred to as "RF heating". In general it has been found that this RF heating raises the equilibrium ion temperature of very small collections of ions to about twice that of the buffer gas[3,4].

The ion temperature determines the area of the action diagram of the macromotion. (Being coherent the RF motion does not contribute to the action area, as shown by the fact that the RF distortion does not change the area of the action ellipse.) Specifically, the density of the action diagram is the gaussian

$$\frac{d^2N}{dxdp_x} = \frac{N\omega}{2\pi kT} \; e^{-\frac{m\omega^2}{2kT}\left(x^2+\left(\frac{p_x}{m\omega}\right)^2\right)} .$$

The standard deviations of this gaussian in the displacement and momentum coordinates are

$$\sigma_x = \frac{1}{\omega}\sqrt{\frac{kT}{m}} \quad ; \quad \sigma_{p_x} = \sqrt{mkT} .$$

Taking the significant part of the action diagram as that extending out to two sigma in both the displacement and the momentum coordinates, thereby accepting about 87% of the total collection, the action area becomes

$$S = 4\pi \frac{kT}{\omega} \quad .$$

In the ISOLTRAP cooler system an ion of mass 100 amu will have a macromotion with an angular frequency of about 0.5 radians per microsecond. For such ions cooled to twice the temperature of the buffer gas, and accepting about a 20% increase in the effective area of the action due to the rapidly rotating RF distortion, the transverse action area of an extracted bunch is

$$S \approx 0.5\pi \; eV\text{-}\mu S$$

The transverse emittance of such a bunch reaccelerated to a momentum p_z is

$$\xi = \frac{S}{p_z} \quad .$$

The p_z of 100 amu ions accelerated to 50 keV is about 300 eV-µs/mm. The emittance of a bunch of such ions extracted to this energy from the ISOLTRAP cooler is then

$$\xi \approx 1.5\,\pi \text{ mm–mrad}$$

and, from the equation for the standard deviation of the radial action density, the diameter of this beam is effectively about 2 mm.

However, this analysis does not take into account any space-charge effects. Early work by Kim[3], who built the first RFQ beam cooling system at McGill, showed that the effect of space-charge was to increase the ion temperature of the beam by an amount that, at low beam currents, was proportional to the beam current. The ion temperature at very low beam currents (< 0.1 nA) was 0.038 eV while the temperature at 1 nA was 0.054 eV. This temperature increase is in keeping with the simple space-charge model of Dehmelt[1] for Paul traps. In that model there is no macromotion, *i.e.,* the ion temperature is zero, and the RFQ field provides an average radial force that exactly counterbalances the repulsive electric field of the space charge. This radial force is proportional to the radius at which it acts on the ion cloud. Since the space-charge field of an ion cloud of uniform density is also proportional to the radius at which that field is evaluated, the RFQ restraint results in a uniform density ion cloud. The radius of the ion cloud will therefore be proportional to the cube root of the number of ions in the cloud.

While Dehmelt's model includes no temperature effects it does indicate how RF heating should be related to the number of ions in the cloud. The RF velocity at the edge of the ion cloud will be proportional to the radius of that edge, and therefore proportional to the cube root of the number of ions. Since the energy of the RF motion, which is the source of RF heating, is proportional to the square of the RF velocity the rise in temperature with number of ions in the collection should be proportional to the 2/3rds power of that number. This is indeed what was observed by Lunney[4] at McGill, in early work on the temperature of ions in a Paul trap.

Similarly for a beam under RFQ restraint. For a column of ions of uniform density the radial space-charge field at any point within the cloud will also be proportional to the radius at the point. For constant velocity along its axis the restrained beam will therefore also be of uniform density. However, now the radius of the restrained beam will be proportional to the square root of number of ions and so the rise in temperature due to space charge should be simply proportional to the ion current, in keeping with Kim's results. Since for given confinement conditions the radius of the ion beam will be proportional to the square root of the ion temperature that radius will also be proportional to the square root of the beam current.

The actual proportionality constant of the beam temperature relative to its current is difficult to estimate by modeling and has only been determined experimentally (by Kim) for beams of up to 1 nA. But taking the liberty of extrapolating that result, *i.e.,* 0.025 eV/nA, indicates that at 10 nA the beam temperature would be of the order of 0.25 eV, resulting in a beam diameter that would be about √5 times that for low beam currents (~2 mm), or about 5 mm. Taking into account the RF distortion of the action ellipses this would be about the maximum size beam that could be accepted by the ISOLTRAP cooler. Handling higher beam currents would therefore require higher power RFQ confinement.

Extrapolating to a High Performance System

Doing the math on the simple space-charge model of an ion beam under RFQ confinement shows that, for a given ion species the beam diameter due to space charge should have the proportionality

$$\text{Diameter due to space charge} \propto \frac{\sqrt{i}}{\sqrt[4]{K.E.}\;\omega_M}$$

where ω_M is the angular frequency of the macromotion of the RFQ confinement and $K.E.$ is the axial energy of the ions in the beam. Because of the relationship to the 4th root of the axial energy of the beam there is little to be gained by pulling the ion faster through the gas since this would itself introduce intolerable heating and radial dispersal of the beam. Confining an intense beam therefore requires increasing the macro frequency in proportion to the square root of the beam current. Taking 1 μA as a benchmark would therefore require increasing the macro frequency by a factor or 10.

The angular macro frequency is related to the RFQ confinement parameters as

$$\omega_M \propto \frac{V_{RF}}{r_o^2 RF}$$

where V_{RF} is the amplitude of the radiofrequency applied across the confinement electrodes, RF is that frequency and r_o is the minimum distance from the beam axis to the confinement electrodes. What is required is then a judicious selection of these parameters to achieve the desired macro frequency.

However, increasing the amplitude of the RF requires a concurrent increase in the radiofrequency. This is because the q parameter of the RFQ confinement must be kept within reason, otherwise the RF distortion of the action ellipse becomes unacceptable, and could even lead to macromotion instability if too high. That parameter is related to the RFQ parameters as

$$q \propto \frac{V_{RF}}{r_o^2 RF^2} .$$

So if r_o is unchanged then the radiofrequency should be increased in proportion to the square root of the RF amplitude. A set of ball-park figures for increasing the macro frequency by a factor of 10 over that of the ISOLTRAP system would then seem to be

$$\text{RF amplitude} - \times 70 \longrightarrow 10\text{ kV}$$

$$RF \quad - \times 15 \longrightarrow 15\text{ MHz}$$

$$r_o \quad - \times 2/3 \longrightarrow 4\text{ mm}$$

With these parameters the q factor would decrease to 70% of that for the ISOLTRAP system, which would have the benefit of decreasing the RF distortion of the action ellipses during the deceleration and cooling of the incoming beam.

Work by Gianfrancesco[5] at McGill has shown that 10 kV potentials across small electrode structures are quite feasible. In fact, potential differences of over 20 kV were supported across gaps of less than 1 mm. What is required is very clean highly polished electrodes and smooth geometries. It was seen that the electric fields that created breakdown actually increased with the presence of helium as a buffer gas, a fact fairly well known in high-powered accelerator engineering where it is attributed to electrode cleaning by sputtering in the helium. For the structure tested at McGill, a simple RFQ linear trap of a set of three quadrants with an r_o of 6 mm, the resistance to an RF discharge persisted at up to helium pressures of about 50 Pa (0.5 mbar).

Schematic of a Proposed System

One of the problems with high-amplitude RF in an RFQ cooler system is that of superimposing DC potentials of only several volts on electrodes under such high RF potentials. Gianfrancesco[6] has shown that this is feasible by using a resonant circuit to generate the RF potentials while feeding the DC potentials through leads running through the interior of the RF conductor (fig. 5).

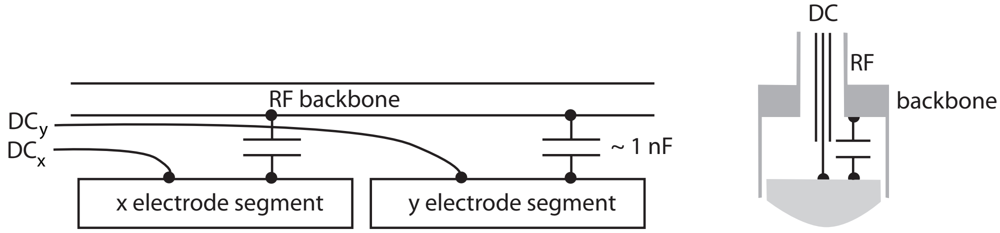

Fig. 5. A schematic of a scheme for superimposing a small DC potential on a large RF potential.

However, even with the relatively low capacitance expected of the electrode configuration RFQ beam confinement a resonant circuit is required to achieve an RF potential of 10 kV without exorbitant RF power. The reason for increasing the *RF* over that which would make the *q* factor the same as for the ISOLTRAP system is to make the RF circuit more amenable to transmission line technology, which can give a high Q-factor for the resonant circuit. For the bipolar electrode configuration of an RFQ ion guide the circuit would be a half-wave line with the RF feed coupled into the node of that line, effectively making it two quarter-wave resonators in anti-phase (fig. 6).

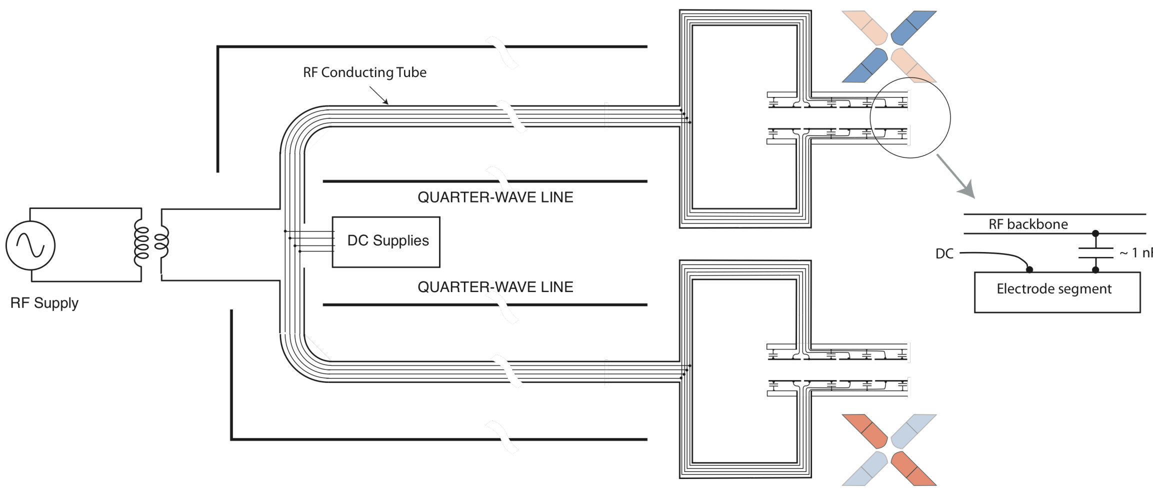

Fig. 6. A schematic of a scheme for driving an RFQ beam cooler based on a half-wave transmission line. Cross-sections of the RFQ electrode configurations showing the electrode pairs that are fed by the opposite ends of the half-wave transmission line are shown in the inserts.

A half-wave transmission line for coupling a load of 400 pF at each end, a load that is expected to be representative of RFQ beam cooler electrodes, has been constructed at McGill using standard 4-inch aluminum box channel with an inner conductor of standard 1-1/8 in. OD copper tubing (fig. 7).

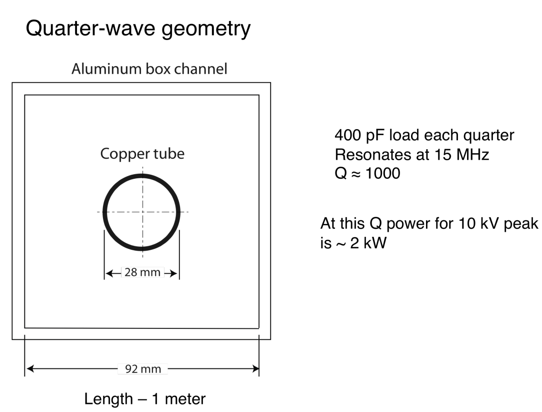

Fig. 7. A cross-section of one side of a mock-up half-wave transmission line for driving an RFQ beam cooler system. The length given is for each quarter wave.

With 400 pF capacitance loading at each end this half-wave transmission line was found to resonate at about 15 MHz with a Q-factor of almost 1000. Using the proper loop at the node of the resonator to couple a 50-ohm RF generator to the system gave an RF amplitude of about 500 Volts across the ends of the half-wave with 50 watts of RF power. This indicates that about 2 kW of power would be needed to achieve 10 kV of RF amplitude. A cross-section of a suggested layout of a half-wave driven RFQ beam cooler system is shown in fig. 8.

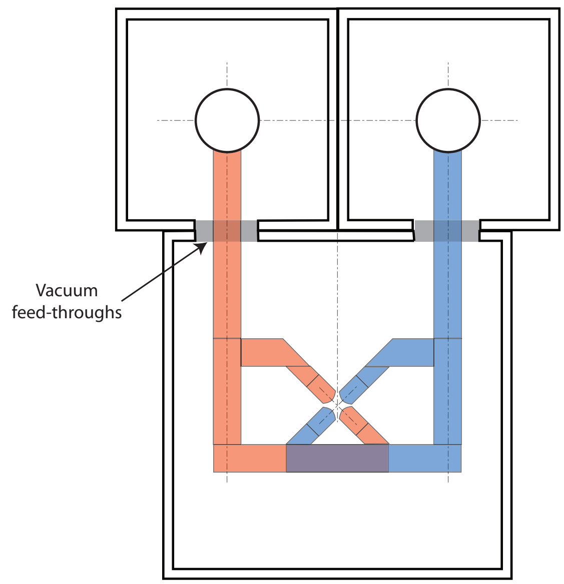

Fig. 8. A cross-section of a suggested configuration for an RFQ beam cooler driven by a half-wave resonator.

Incidentally, the 1-1/8 in. copper tube would have adequate internal volume to funnel the DC leads to the RFQ electrodes. However, there may have to be more finagling to continue the path of these leads into the vacuum to the various RFQ electrode quadrants.

Of course, achieving a Q-factor of 1000 with the a real set of RFQ electrodes, which could end up being distributed over a length of up to a meter, would require careful design of the path for the RF current along the length of those electrodes so as to keep the resistive losses as low as possible.

There is another benefit of a high-Q system above that of reducing the RF power. One of the problems with driving an RFQ cooling system to high RF levels is that imbalances in the potentials on the electrodes can lead to significant RF heating. The work of Gianfrancecesco showed that there was heating from harmonics in the waveform of the RF. This was probably because of imbalance of the waveform harmonics. Minor imbalance of the fundamental, which had been tuned out to within about 2%, should not induce RF heating because the ions will automatically center at the bottom of the quadrupole potential even when it is off the axis of the system. However, an imbalance of a harmonic of the waveform, which would be difficult, if not impossible, to tune out simultaneously with the fundamental, could cause heating of the ions sitting at the bottom of the quadrupole. A high-Q RF system will minimize such harmonics.

The need for high-Q RF suggests a consideration of a superconducting system. Such a system should be possible for cooling systems using helium as a buffer gas, one of the benefits being the possibility of producing very cold beams. However, such a system might not be feasible for intense beams because of the possibility of contamination of the electrodes. Certainly, a superconducting system is not one that should first be considered.

Conclusions

The construction of an RFQ beam cooling system for ion beams of up to 1 μA should be feasible. However, its design will require more professional RF engineering than for the present systems.

References

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