

# STUDY OF THE RFQ BEAM COOLER FOR SPES PROJECT

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## Abstract

In the framework of the SPES project [1], the radioactive ion beams transport is under study in order to evaluate the transmission efficiency and the final quality of the delivered beams in terms of mass resolution and longitudinal energy spread. In particular the high resolution mass spectrometer needs a beam emittance of the order of  $3\pi$  mm mrad and an energy dispersion of about 1 eV to get the minimum resolving power of 20'000. These requirements will be fulfilled with the radio frequency quadrupole (RFQ) beam cooler device [2].

The gas-filled, RFQ is a device whereby a previously decelerated, low energy ( $E < 100\text{eV}$ ) beam is thermalized via successive collisions with an inert buffer gas. This process allows to decrease by the energy exchanging with the gas molecules, both the radial momentum and the longitudinal energy dispersion of the ions passing through the RFQ.

The preliminary design of the device is carrying on at LNL since 2011 and the feasibility study is funded by V committee of INFN in the framework of REGATA experiment. Both beam dynamics study and the electromagnetic design are presented in this paper.

## PRINCIPLES OF THE RFQ COOLER

The exotic beams are produced in the target station [3] by means of the ISOL technique and they are preselected in mass with a resolution of 1 in 400 by a Wien Filter and a set of double 90 deg dipoles placed downstream the target device. Therefore, the  $Q=1+$  radioactive ion beams are delivered at the energy of 60 KV and with a transversal emittance of  $30\pi$  mm mrad along the beam transport line and then injected into the RFQ beam cooler device which provides the reduction of a factor 10 of the above-mentioned emittance and to achieve some eV of energy spread.

In an RFQ cooler the temperature of the ion beams is reduced via successive collisions with the atoms of a buffer gas. By applying the RF field to a quadrupole electrode structure, one can provide a radial force which counteracts the dispersion of the ions caused by the cooling process. The principle of the confinement is the same as in quadrupole mass filter. An RF voltage with amplitude  $V$  and frequency  $\omega_{RF}$  is applied to the rods of a quadrupole in opposite of phase. The motion of the ions in the RF quadrupole is governed by the so-called Mathieu parameter  $q$  [2]

$$q = \frac{4 \cdot Q \cdot V}{m \cdot r_o \cdot \omega_{RF}^2} \quad (1)$$

Where  $Q$  is the charge and  $m$  the mass of the ion, and  $r_o$  is one half of the distance between two opposite rods. The ion motion is stable with  $0 < q < 0.9$  [2]. The depth of the potential well is given by

$$D = \frac{q \cdot V}{4} \quad (2)$$

The so-called pseudopotential approximation is valid with low values of  $q$  ( $< 0.5$ ) where, without interaction of the buffer gas, the ion motion can be regarded as simple harmonic oscillation at macromotion frequency

$$\omega_o = \frac{q}{2 \cdot \sqrt{2}} \omega_{RF} \quad (3)$$

The ions have additional oscillation, the so-called micromotion which comes from the driving RF field. The micromotion has the same frequency of the RF field and amplitude proportional the electric field being zero in the axis and increasing linearly with the radius. At low values of  $q$  the micromotion is just a ripple on the top of the macromotion, but above  $q=0.5$  the micromotion amplitude becomes the same order as the macromotion amplitude, and the two motions became indistinguishable as shown in Fig. 1.

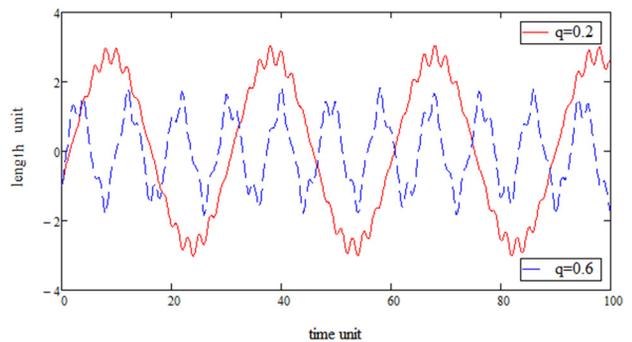


Figure 1: Typical motion of an ion under RFQ confinement. The red lines shows the trajectory on the ion by setting the parameter  $q=0.2$ . In this case the superimposition of the micro and macro motion is quite evident. The blue dot line shows the trajectory of the ion increasing the parameter  $q=0.6$ . In this case the two motion become indistinguishable.

A necessary condition for an efficient cooling is that the buffer gas atoms are sufficiently lighter than the mass of the ions. It was demonstrated [4] that in the RFQ environment, the collisions of the ions with heavier mass result in a net ions heating whereas collisions with molecules lighter than the confined ions result in cooling towards the temperature of the background gas itself. In

this case, the micromotion is only slightly modified in phase and amplitude while the main motion is dumped exponentially.

Once the ions are stopped and cooled within the buffer gas they must be dragged through the remaining gas in the path to the exit. This is accomplished by a longitudinal component of the electric field provided by DC potentials applied to the successive RFQ segments.

## PRELIMINARY DESIGN

The RFQ beam cooler device is composed by 3 main sections: the deceleration system, which provides the reduction on the energy of the incoming beam from 60 keV to some hundreds of eV; the confinement and cooling section placed on a 60 kV high voltage platform, where is located the RFQ and where the buffer gas is injected in order to get a pressure within  $0.5\div 3$  Pa; finally the acceleration section where the cooled beam is extracted and accelerated up to 60 keV. The electromagnetic field configuration was studied by the use of 3D FEM code OPERA, which allows to define the preliminary dimension and the operating parameters. The beam dynamic was studied by the dedicated code SIMION ver 8 in order to taking into account the collisional effects and to simulate the cooling process. In this preliminary design phase the space charge effect on the transport of high intensity beams has been neglected.

### Injection System

By using a multiple electrode configuration the ions are decelerated to about 100 eV before to entry into the cooling section. Such as deceleration system must be designed to provide the best matching with the acceptance of the RFQ.

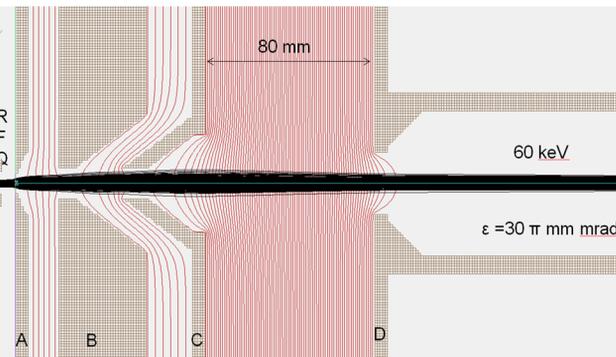


Figure 2: The SIMION beam transport simulation for the  $^{133}\text{Cs}^{1+}$  beam along the deceleration system. This is composed by 4 stage of electrodes at different voltage: A=59.8 kV, B=56 kV, C=52 kV, D=0 kV. As shown the waist is placed as close as possible to the RFQ entry in order to match the acceptance ellipse.

The lens system focuses the beam to a spot of 2 mm in diameter and 0.3 mrad of divergence as shown in Fig. 2. The electrodes are shaped in order both to optimize the beam envelop along the section and to minimize the

length of the last drift before entry into the RFQ chamber. In fact, because of the low energy of beam passing through the A-B electrodes, its interaction with the residual gas coming from the cooling chamber through the pinhole causes the loss of some particles.

### Confinement and Cooling Section

The RF quadrupole consists of four cylindrical rods of 9 mm of diameter. The rods are 700 mm length and they are divided into 10 segments of 69.5 mm each. The segmentation is used for producing an axial field which provides the drag force needed to bring out the cooled beam. The total voltage applied along the segmentation is 100 V. The distance between the opposite pair of rods is  $2r_o=8$  mm.

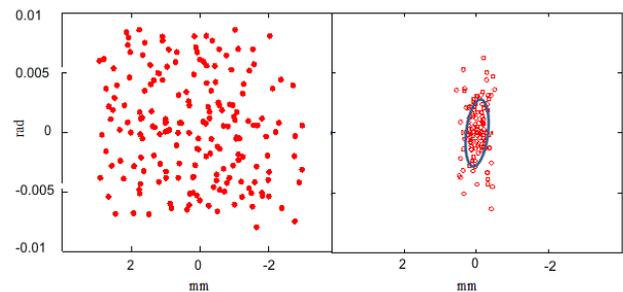


Figure 3: The plot shows the effect of the cooling process on the transversal emittance of  $^{133}\text{Cs}^{1+}$  ion beam calculated by the SIMION code. On the left side the starting emittance of  $30 \pi$  mm mrad and on right side the reduced one by a factor 10. The operational parameters are  $V_{RF}=1.5\text{ kV}$ ,  $f_{RF}=5.57$  MHz,  $P_{He}=2.5$  Pa,  $q=0.22$ , transmission = 90%.

The applied RF voltage and the operating frequency depends on the ion mass delivered which varies within 9-170 UMA and on the current intensity of the incoming beam. Since we expect to operate up to 50-100 nA of beam current, a relatively strong RF confinement is needed to overcome space-charge effects. Therefore we plan to operate within the range of 1-3 kV. Once fixed the stability region as  $0.2 < q < 0.4$  in order to achieve the maximum transmission efficiency, by the equation (1) one can get the operating RF frequency range: from 3 MHz for heavy ion ( $A=200$ ) to 7 MHz for lightest ( $A=10$ ).

He at 273 °K was chosen as buffer gas for ion cooling. The operational gas pressure varies from 0.5 to 3 Pa, depending on the ion mass of the beam whose emittance has to be reduced and on the RF voltage applied to the quadrupole. By the preliminary results given by SIMION code using the hard sphere model to simulate the interaction gas-ion, the cooling process was simulated and a transversal emittance reduction of a factor 8-10 was achieved as shown in Fig. 3.

### Extraction System

Following the cooling process through the RFQ, the

ion beams exit through a 6 mm diameter aperture and then they are reaccelerated to the initial energy by a two stages of electrodes as shown in Fig. 4.

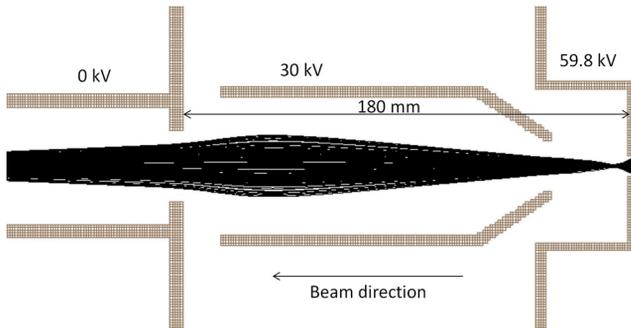


Figure 4: Preliminary layout of the extraction system of the RFQ cooler and the related beam optic. The optimization process of the electrodes is carrying on.

### Vacuum Considerations

The differential pumping system is very crucial for achieving the optimal cooling and transmission efficiency. The gas leakage through the entrance apertures cause the energy degradation of the beam and the related lost due to the scattering with molecules of the residual gas. These harmful effect can be reduced by careful design of the differential pumping system and the optimization of the placement of the injection and extraction devices with respect to the entrance and exit of the vacuum chamber where the RFQ is placed. This design is under study in collaboration with CERN team.

## EXPERIMENTAL SETUP

As mentioned in the previous section, the cooler requires of applying an RF voltage of some kV to the electrodes in presence of a buffer gas pressure of some Pa. This pressure range is near to the minimum of the Paschen curve [5], which states the discharge voltage as a function of the product between pressure and electrode distance.

To evaluate the sustainability of the necessary RF voltage in the operational pressure range we designed (Fig. 5) a test apparatus which will be integrated in an existing vacuum chamber where we can produce the required pressure conditions. A CF150 flange supports the electrodes and allows to change their distance without the necessity to open the chamber. The electrodes are isolated by peek supports. A computer controlled 10kV voltage supply allows to vary the voltage of one electrode while the other remain at ground.

The He pressure in the chamber can be adjusted according to the test request. The system is going to be completed and it will produce the first results next summer.

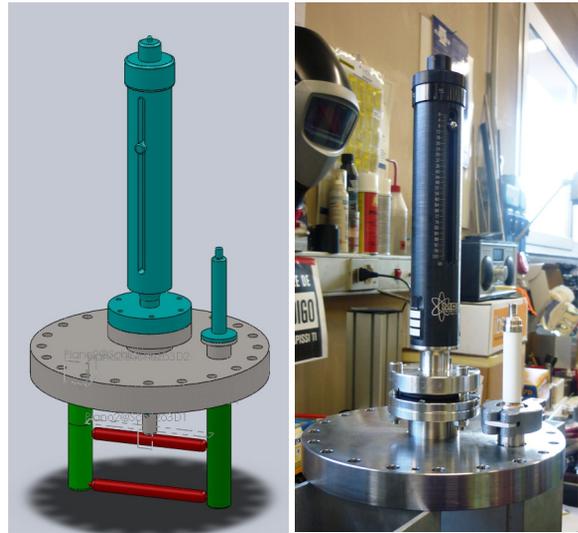


Figure 5: Drawing of the pressure test system and top flange of the apparatus designed for testing conditions of discharges at low He pressures. The discharge can be a critical issue for the operation of a beam cooler for high intensity beams.

## CONCLUSIONS

The preliminary design of the RFQ beam cooler for SPES project started this year and it is carrying on by the LNL team. The electromagnetic layout and the first results about the beam dynamic were presented in this report. The operational parameters of the device were chosen and the process of optimization of them is going on. Once this first phase of the study is accomplished out, the beam dynamic will be completed by the introduction of the space charge effects.

## REFERENCES

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