INTRODUCTION

In the framework of the SPES project, the radioactive ion beam 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 $<3 \pi \text{mm-mrad}$ 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 [1].

The preliminary design of the device is being developed at LNL since 2011, and the results of the simulation study of the electromagnetic field and of the beam dynamics are presented in this report.

PRINCIPLES OF THE RFQ COOLER

The exotic beams were produced in the target station by means of the ISOL technique and preselected in mass with a resolution of 1 in 400 by a Wien Filter and a set of double 90 degrees dipoles placed downstream the target device. Therefore, the Q=1 radioactive ion beams were delivered at the energy of 60 KV and with a transversal emittance of $30 \pi \text{mm-mrad}$ 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 filters: an RF voltage with amplitude $V$ and frequency $\omega$ is applied to the rods of a quadrupole in opposition of phase. The motion of the ions in the RF quadrupole is governed by the so-called Mathieu parameter $q[1]$

A necessary condition for an efficient cooling is that the buffer gas atoms must be sufficiently lighter than the mass of the ions. It was demonstrated [2] that in the RFQ environment, the collisions of the ions with heavier mass results in a net heating of the ions at all temperatures 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 which depends on the RF frequency, is not interrupted by collisions but 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 OF THE RFQ COOLER

The RFQ beam cooler device consists of 3 main sections: the deceleration system, which provides the reduction of the energy of the incoming beam from 60 keV to some hundreds of eV; the confinement and cooling section placed on a 59.8 kV high voltage platform, where the RFQ is located and where the buffer gas is injected at high pressure (0.5-2.5 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 dynamics was analyzed by the code SIMION version 8, in order to take into account the collisional effects and to simulate the cooling process. In this preliminary phase the space charge effect on the transport of high intensity beams has been neglected.

The Injection System.

By using a multiple electrode configuration the ions are decelerated to about 100 eV before entering the cooling
section. Such a deceleration system must be designed to provide the best matching with the acceptance of the RFQ. The lens system focuses the beam to a spot of 2 mm in diameter and 0.3 mm rad of divergence as shown in figure 1. The electrodes are shaped in order to optimize the beam envelope along the section and 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 (see figure 1), the interaction with the residual gas coming from the cooling chamber through the pinhole causes the loss of part of the particles.

Confinement and Cooling Section.

The RF quadrupole consists of four cylindrical rods of 9 mm of diameter. The rods are 700 mm long and divided into 10 segment of 69.5 mm each. The segmentation is used electrically to produce an axial field to provide 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 pairs of rods is 2r_e=8 mm.

The applied RF voltage and the operating frequency depends on the ion mass delivered, which varies within the range: 10 + 200 u, and on the current intensity of the incoming beam. Since we expect to operate up to 500 nA of beam current, a relatively strong RF confinement is needed to overcome space-charge effects. Based on the recent results [3] obtained by the team of the Laboratoire de Physique Corpusculaire (Caen) involved in the commissioning of the SPIRAL Cooler, we plan to operate within the range of 0.5-2.5 kV. Once the stability region is fixed as 0.2 < q < 0.4 in order to achieve the maximum transmission efficiency, one can get the operating RF frequency range: from 3 MHz for heavy ion (A=200) to 25 MHz for lightest ion (A=10).

On the basis of the preliminary results given by the SIMION code and 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 figure 2.

The Extraction System.

Following the cooling process through the RFQ, the ion beams exit through a 6 mm diameter aperture and they are reaccelerated to the initial energy by two electrodes as shown in figure 3.

Vacuum Considerations.

The differential pumping system is crucial for achieving the optimal cooling and transmission efficiency. The gas leakage through the entrance aperture causes the energy degradation of the beam and the consequent particle losses due to the scattering with the molecules of the residual gas. These harmful effects can be reduced by the careful design of the differential pumping system and the optimization of the positioning of the injection electrodes with respect to the entrance of the vacuum chamber where the RFQ is placed.

CONCLUSIONS

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

As a buffer gas for ion cooling, the He at 293 K was chosen. The operational gas pressure varies from 0.5 to 2.5 Pa, depending on the ion mass whose emittance has to be reduced and on the RF voltage applied to the quadrupole.

Fig. 2: The plot shows the effect of the cooling process on the transversal emittance of $^{133}$Cs$^{1+}$ ion beam calculated by the SIMION code. On the right side the starting emittance of 30 π mm rad and on right side the reduced one by a factor 10. The operational parameters are $V_{RF}$= 1.5kV, $f_{RF}$=5.57 MHz, $P_{in}$=2.5 Pa, q=0.22, transmission = 90%.


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