Simulations of high intensity ion beam RFQ cooler for DESIR/SPIRAL 2: SHIRaC

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ABSTRACT: SHIRaC is a buffer gas radiofrequency quadrupole cooler, part of SPIRAL 2 facility, at GANIL in France. It is designed to cool low energy ion beams with emittances up to $80 \pi.\text{mm.mrad}$ and currents up to 1 $\mu\text{A}$. It is devoted to reduce the beam parameters; less than $3 \pi.\text{mm.mrad}$ of emittance and around 1 eV of spread energy, and to transmit more than 60% of ions. However, to achieve the least possible emittance, spread energy and ion transmission, the space charge has been overcome using high confining RF amplitude.

Numerical simulations have been developed in order to study and evaluate the space charge effects on the beam parameters and the ion transmission. The simulation results have shown that the main degradations of these parameters stem from this effect. The ion transmission decreases progressively with the beam current and it nevertheless remains above 65%. The emittance and the spread energy increase with the beam current while staying below 2.4 $\pi.\text{mm.mrad}$ and 5.9 eV respectively.

KEYWORDS: Instrumentation for radioactive beams (fragmentation devices; fragment and isotope, separators incl. ISOL; isobar separators; ion and atom traps; weak-beam diagnostics; radioactive-beam ion sources); Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Beam Optics; Beam dynamics

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1 Introduction

The DESIR (Désintégration, Excitation et Stockage d’Ions Radioactifs) facility is a low energy, up to 60 KeV, beam experiment [1]. It is part of the new equipment necessary for the exploitation of the radioactive ion beams produced by SPIRAL2 (Système de production d’Ions Radioactifs en Ligne de 2ème génération) [2, 3] at GANIL (Grand Accélérateur National d’Ions Lourds), France. SPIRAL2 facility is designed to extend nuclear physics research by producing a variety of rare and exotic ion beams with intensity orders of magnitude beyond those currently available [4] and with emittances around 80 π.mm.mrad [5]. The construction of DESIR will start in September 2015.

Because the increasing intensities of radioactive ion beams leads to increased isobaric contaminations [6], DESIR includes an important instrument for beam purification: a high-resolution mass separator (HRS) for high-intensity beams. This HRS has been developed in the CENBG laboratory

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located in Bordeaux (France) and its nominal running requires ion beams with an emittance of less than $3 \pi \text{mm.mrad}$ and with a longitudinal spread energy around 1 eV [7, 8].

Recent developments of the Radio-Frequency Quadrupole Cooler (RFQC) open the possibility of reducing beam emittance upstream of the HRS to increase the resolving power [9]. Therefore, the HRS of DESIR is preceded by a buffer gas RFQC that will provide the lower-emittance beams necessary for higher mass resolving power.

A detailed introduction of RFQCs has been presented in several references [10–15]. It consists of a quadrupole on which an RF oscillating potential with opposite phase is applied (RFQ). This provides a radial confinement of ions. The ion full-motion into the quadrupole can be composed of two components: the micro-motion and the macro-motion [10, 16]. The transverse ion motions are governed by the so-called Mathieu equations [11, 12, 17] and their stability is insured by the Mathieu parameter $0 < q < 0.908$ which is defined by the following formula [12, 16]:

$$q = \frac{4eV_{RF}}{mr_0^2w_{RF}^2}$$  \hspace{1cm} (1.1)

In this expression $e$, $m$, $V_{RF}$, $w_{RF}$ and $r_0$ are respectively, the elementary charge, the ion mass, the amplitude of RF voltage, the angular frequency of RF voltage and the quadrupole inner radius.

A light buffer gas, typically Helium, is injected in the RFQ. The ions will lose energy in collisions with buffer gas atoms and the amplitude of the oscillation of ions will be reduced. The ions are thus driven to the centre of the quadrupole and the ion beam emittance is progressively reduced. Finally the ions will reach a thermal equilibrium with the buffer gas. The cooled ions will then be guided to the quadrupole exit.

The present RFQCs handle ion beams with intensities not exceeding few tens nA. Confining RF voltages with amplitude less than 1 kV and with frequency less than 1 MHz are sufficient to provide an optimum cooling. In order to fulfill the needs of SPIRAL 2, which aims at providing high-intensity beams of rare isotopes, it is desirable to increase the beam intensity limit of such devices from typically several tens of nanoamperes to microamperes. This requires the use of high-voltage radiofrequencies to overcome the space charge effects of high beam currents [18]. A buffer gas RFQC named SHIRaC (SPIRAL2 High Intensity Radiofrequency Cooler), dedicated to this purpose, is under development at the L.P.C (Laboratoire de Physique Corpusculaire) in Caen (France). It will be located at the SPIRAL 2 production building, as shown in figure 1.

The HRS requirements give the following specifications for SHIRaC: geometric transverse emittance $\varepsilon_{60\text{keV}}$ (which will be subsequently simply referred to as emittance) less than $3 \pi \text{mm.mrad}$ at 60 keV, longitudinal energy spread $\Delta E$ (which will be equally subsequently referred to as energy spread) of 1 eV and ion transmission more than 20% for ions with mass $m > 12$ a.m.u, more than 40% for $m > 40$ a.m.u and more than 60% for $m > 90$ a.m.u [7].

This paper reports on simulation studies of space charge effects on both the ion beam parameters (the geometric transverse emittance $\varepsilon_{60\text{keV}}$ and the longitudinal energy spread $\Delta E$) and the ion transmission along the RFQC beam line. To that end, three stages of simulations will be presented: one simulating the injection process, one simulating the cooling process and one simulating the extraction process. At the exit of each stage both the beam parameters and the ion transmission are presented and their dependencies on the beam currents are discussed. Finally, simulation results of the cooling of ions for different mass levels are outlined.
2 Space charge consideration

As we previously saw, the main specificity of SHIRaC is the ion beam intensity which is higher by a magnitude of 10–100 than in the present technology. That increases the space charge effects. In this section, we will present theoretical and computing considerations about this effect and its main influences on the beam parameters.

2.1 Space charge field compute

In pressure environment, it is very difficult to deal with the individual interaction between the ions, even with the fastest computers [19]. A few calculation methods are available, such as the tube-method and the ions-cloud method [20–22], to give a quick and a rough estimate of this field.

2.1.1 The ion-cloud method

This method simply assumes that the real particles are charge clouds surrounding points. This means that each set of real particle can be assimilated to a reduced set of simulated particles. The distribution of the total charge among the individual simulated particles is controlled by the charge-weighing-factor (CWF) specified for each particle in the particles’ definition. The purpose of the CWF is to control the relative number of real particles for each simulated particle. Thus, the repulsions amount between millions of real particles may be simulated to only a few hundreds of simulated particles. The interactions between the simulated particles are governed by coulomb’s law. The mathematical description is again given in the reference [21].

This method can be used in pressure environment conditions because it is based on a time coherent approach [19, 21].

2.1.2 The tube method

The tube method is a better approximation to the space-charge of a beam in computational simulations of charged particle systems. It makes use of the trajectory steps that result from the process
of trajectory integration. The space-charge associated with each step of each trajectory is assigned to a narrow cylindrical tube that surrounds the step. The total space-charge of a beam is then the sum of the charges in all the resulting the tubes.

The tube method is particularly useful for simulating the space-charge of beams that are very narrow compared with their length. Using the Gauss theorem, we obtain the following equations of the space charge field:

\[
\begin{align*}
\text{r} < r_s & : \vec{E}_{sc} = \frac{I r}{2 \pi \epsilon_0 v r_s} \vec{u}_r \\
\text{r} > r_s & : \vec{E}_{sc} = \frac{1}{2 \pi \epsilon_0 v r} \vec{u}_r
\end{align*}
\]

(2.1)

(2.2)

Where \( \epsilon_0 \) is the constant vacuum permittivity, \( v \) is the ion velocity, \( r_s \) is the mean charge distribution radius, \( I \) is the beam current and \( r \) is a radial position.

These equations show direct competition between the beam current and the ion velocities: the slower the ions, the higher the effect becomes. Along the cooling part, after successive collisions with the buffer gas molecules, the ions will be slowed down from a few hundred eV to about 1 eV [23]. That might lead to strengthen the space charge effects, particularly at the limit of the cooling part.

2.2 Space charge effect on the cooling

At the quasi-equilibrium state into the RFQ, the problematic of space charge and its importance on the cooling is shown by the following equation [24, 25]:

\[
\frac{2e^2 V_{RF}^2}{mr_s^2 \epsilon_0^2 v^2} = 2k_B T + \frac{eI}{4 \pi \epsilon_0 v}
\]

(2.3)

Where the terms denote respectively the confinement term, the thermal term and the space charge term.

Both the ion velocity and transverse size of ion beam (the \( r_s \) term) decrease progressively during the cooling process. Therefore, the thermal and the confinement terms decrease whereas the space charge term increases. The only way to overcome the space charge effects is to increase the confinement term by increasing the RF voltage amplitude [18].

The competition between the space charge and the RF voltage amplitude leads us to study the RFQ confinement limit.

2.3 Space charge effect on the confinement capacity

In the Dehmelt concept, the RF voltage effect on the cooling is equivalent to a pseudo-potential well which traps the ions along the quadrupole [26]. This well is assumed to be a harmonic oscillator one of depth \( D \) with a maximum allowable of [27]:

\[
D_{max} = \frac{q V_{RF}}{4}
\]

(2.4)

The space charge potential can be assimilated to a harmonic oscillator well of depth \( D_{SC} \). This depth can be deduced from equation (2.1) and is expressed as:

\[
D_{SC} = \frac{I r^2}{4 \pi \epsilon_0 v r_s^2}
\]

(2.5)
Its maximum is:

\[ D_{SC,\text{max}} = \frac{I}{4\pi \varepsilon_0 \cdot v} \]  

(2.6)

Thus, the space charge effects on the cooling are manifested by the reduction of depth D by
the space charge contribution \( D_{SC} \) [28]. Owing to this effect, the RFQ has a limit in the maximum
intensity of the ion beam that can be manipulated [29, 30], which can be expressed by [31–33]:

\[ I_{\text{max}} = \frac{2\varepsilon_0 D_{\text{max}}}{\pi \cdot r_s^2 \cdot r_0^2 \cdot v} \]  

(2.7)

As an example, if we consider Cs\(^+\) ions beam at 1 eV in a RF potential of 2.8 kV at 4.5 MHz
\((q=0.4)\) in a 5 mm inner radius quadrupole, this model shows that it's possible to confine around
1 \( \mu \)A.

3 Optics system of SHIRaC

The RFQ Cooler system was used in several recent works. As all the RFQC devices, SHIRaC
can be divided in three parts: deceleration and injection part, cooling part, and extraction and re-
acceleration part [11]. These parts have to ensure an efficient transmission of SPIRAL2 ion beams.
We will discuss the purpose of these parts and present their dimensions.

3.1 Deceleration and injection part

To efficiently cool typical SPIRAL2 beam, the injection energy that will bring the ions to the
cooling part should of few hundred eV [10, 34]. Therefore, the relatively high energy of beam
should be decelerated using a DC electric field. The deceleration can be done by the injection plate
electrode setting at high voltage (HV) with the platform and the grounded electrode setting at the
mass, figure 2.

\[ HV=59.860 \text{ kV} \]

Figure 2. Layout of the deceleration and injection part.

The injection plate electrode has a very small hole, 8 mm diameter aperture, in order to effi-
ciently capture the ion beam and to create a differential pumping between the RFQ and the injec-
tion part.
3.2 Cooling part

The cooling part consists of the main RFQC chamber, setting at HV. It encloses the buffer gas and the radiofrequency quadrupole (RFQ). It is devoted to trap efficiently the injected beam and to cool it progressively with the buffer gas. To guide the ions along the RFQ up to the extraction cell, the RFQ electrodes are segmented and a DC axial potential is applied on these segments [35, 36]. For buffer gas pressures into the RFQ (RFQ pressure) of a few Pascal, the quadrupole length should be in the range of 300–1000 mm [18].

The RFQ structure itself is designed to be slightly larger in the radial direction compared to existing similar devices, to be able to capture higher intensities and large emittance beams. This design is optimized by SIMION to cool typical SPIRAL2 beams with a buffer gas pressure of few Pa. Therefore, we have chosen a length of 725 mm so 18 segments of 40 mm of length. Depending on the compromises taken in the capture of the large incoming beam, the handling of the high intensity beam and the use of the higher potential well depth, this can be provided in quadrupole inner radius of 5 mm.

3.3 Extraction and reacceleration part

The optics system, which extracts and accelerates the ion beam back to the same energy as that of the injected beam, is based on a similar layout as the deceleration and injection system, figure 3. Numerical simulations, done by SIMION, were carried out to aid in the design of this system. The beam is extracted from the cooling part through the extraction plate. Once it passes through this plate, it is strongly accelerated by the DC electric field created between the extraction plate and the grounded electrode. The three-electrodes lens is set up to prevent ion losses.

The extraction plate has a very small hole, 6 mm diameter aperture, in order to create a differential pumping between the RFQ and the extraction part.

![Figure 3. Layout of the extraction and re-acceleration part.](image-url)
4 Numerical simulation tools

Simulation of ion motions in electromagnetic field, in gas environment using a number of computer programs is a subject of considerable recent interest. The programs permit calculation of ions trajectories while the ions are subjected to collisions with buffer gas of variable pressure, in variable electric fields provided by the electrodes, in RF electric field (RF ion trap) as well as with the space charge. The mainly differences between the programs is the manner in the treatment of ion-atom interactions mechanism. Several physics models can be used to deal this mechanism.

In order to gain a better understanding of the features of cooled ions, simulations have been undertaken by individual treatments of ion-atom collision models such as the first variable hard sphere (HS1) and the realistic potential (RP) models. Related to the ion trap (RFQC) there are several examples of computer programs using the first model such as the commercial SIMION code [37] and other programs using the second model such as the IonCool code of S.Schwarz (Michigan State University) [38] and the code of B.Bruyneel (IKS Leuven )/J.Szerypo (University of Munich) [13, 39].

HS1 model appears as a first correction to classical hard sphere collision model [10, 37, 40]. It showed a decrease in the average kinetic energy of ions and decomposition of ion movement toward the quadrupole field center [11]. However, it cannot give quantitative accuracy on the cooling process at low ions energy [28]. To avoid the handicap of this model a not hard ion-gas collision model called realistic potential (RP) can be used [11]. For that reason, the cooling process has been simulated using the RP model. However, the injection and the extraction process simulations can be done using the HS1 model.

The simulations described in this work have been realized using two computer programs: a SIMION code using HS1 model and Python code using the RP model. These programs are discussed in the following separate subsections.

4.1 Ion optics modeling program: SIMION 3D

SIMION 3D version 8.0 software is a ray tracing code for three dimensional (3D) simulations [20, 21]. It allows to predict the ions’ trajectories in various conditions in a neutral gas at high pressure, under the influence of electrostatic field and in presence of the space charge [41]. The ion-cloud method for estimating this effect is included in this program. The ion-gas collision model incorporated in this program is the HS1 model [21, 37].

This software has been chosen because it allows, through its interface, to easily define the design of the beam line and to control quickly several parameters such as the buffer gas distribution, the voltages of electrodes, the beam current, and the initial beam parameters [20, 21]. More comprehensive descriptions of the capacities of the SIMION package may be found elsewhere [20, 21].

4.2 Python program

Examination of the cooling process has been undertaken by Python program. Computation for the ions’ trajectories under various conditions was used to account for the effects of ions-gas collisions. These collisions are modeled by the RP model.

The RP model aims to realistically simulate these collisions via (12,6,4) ion neutral molecular interaction potential V(r) describing the interaction of an ion with a molecule at a dis-
tance $r$ [11, 38]:

$$V(r) = \frac{C_{12}}{r^{12}} - \frac{C_6}{r^6} - \frac{C_4}{r^4} \quad (4.1)$$

Where $C_{12}$, $C_6$ and $C_4$ are constants for a given ion-gas. The constants were determined using the mobility data and tables of transport collision integrals for (12,6,4) ion-neutral potential [42, 43]. The constants are $C_{12} = 20580.6 \text{eV}^{12}$, $C_6 = 16.9 \text{eV}^{6}$ and $C_4 = 1.55 \text{eV}^{4}$ for Cs$^+$-He.

The computing of the ions motions is based on the compute of the ions mobility ($K$) which can be deduced from (12,6,4) interaction potential. The ion mobility is calculated as a function of the collisional integral $\Omega(T_{\text{eff}})$ [38]:

$$K = \frac{3eE}{16N} \sqrt{\frac{2\pi(m+M)}{K_BT_{\text{eff}}mm}} \frac{1}{\Omega(T_{\text{eff}})} \quad (4.2)$$

Where $m$, $M$, $N$, $E$, $K_B$ and $T_{\text{eff}}$ are the ion mass, the gas atom mass, the number density of the gas atoms, the energy available in the center of mass system, the Boltzman constant and the effective temperature.

The RP model accuracy may be tested by comparing the calculated mobilities with the experimental mobility data [43]. The mobility in the RP model is 1 to 11% different to the experimental one, figure 4. This error seems to come from the experimental error and the error in the interaction potential form. This agreement test means the reliability modeling of the realistic interaction potential.

The simulation algorithm of the ion motion calculation, in this program, is similar to the one presented in references [44, 45]. This program enables to simulate the cooling process, including the embedded ability to estimate the space charge by the tube-method, while the electric field has an analytical expression.

![Figure 4](image-url)
5 Simulation results

The performance of the RFQC has been studied by simulating the entire ion manipulation process from the entrance of the injection part to the exit of the extraction part.

Three simulation regimes were implemented — one with only the injection optics up to the entrance of the RFQ, one with the ions starting from a point just inside the RFQ and following through to its exit and one with the ions starting from a point just outside the RFQ to the exit of the extraction part. The simulations are used to investigate the ion transmission through each part and the beam parameters (the emittance and the spread energy) after the cooling and the extraction processes. The space charge effects on these parameters are outlined.

The RFQ operates at 4.5 MHz and 2.8 kV RF voltage, which results in \( q=0.4 \). The DC axial guiding field is at 16 V/m. Buffer gas pressure distribution is also included in these simulations. The pressure along the beam line is reduced using a differential pumping system similar to those used in the present devices such as the ISCOOL project [46, 47]. Some first simulations with SIMION show that the RFQ pressure which can provide an optimum cooling is around 2.5 Pa. The resulting pressures at the injection and the extraction parts are respectively, of 0.02 Pa and 0.01 Pa.

5.1 Simulation of injection process

As mentioned in section 3.1, along the injection process the 60 keV ions undergo a deceleration to about 100–200 eV. The simulations of this process can be performed with SIMION. The simulation models the ion motions along the injection part. It was done for an uniform circular distribution of 1000 \(^{133}\text{Cs}^+\) ions in Helium buffer gas. The ions’ initial conditions are determined for ion beam 60 keV of energy, 80 \(\pi\).mm.mrad of transverse emittance, 20 mm of transverse size and a few tens eV of spread energy.

During the deceleration it is important to avoid the losses of ions by choosing the optimum applied voltages on the injection plate and injection electrodes. For that reason, some simulations for current of 100 nA have been done. The simulations showed that using the following voltages: 59.860 kV for the injection plate, 57.800 kV for the first and third electrodes of the lens and 57.700 kV for the middle lens’ electrode, about 98% of beam could be fully injected into the RFQ. The injection plate voltage enables to control the injection energy of the ions into the RFQ. When setting the injection plate voltage at 59.960 kV, the energy of the ions at the RFQ entrance is around 140 eV.

Furthermore, the ion losses can be more significant under the RF phase (due to the high RF amplitude) and the space charge. The first effect is minimized by using a large RF frequency (4.5 MHz) with the lowest RF amplitude [10]. The RF amplitude should allow for an optimum cooling, thus it is convenient to ensure that \( q=0.4 \) hence 2.8 kV. The simulation results of the second effect are illustrated on figure 5. The presence of this effect explains the reduction of the transmission with the beam current. This degradation does not appear to be significant because the energy of ions remains important to counter this effect and less than 7% of ions are lost for beam current up to 1 \(\mu\)A.

The consideration of the space charge effects is relative to the energy of ions and the beam current, equations (2.1), (2.2). Because the energy of ions is more than 100 eV along the injection part, this effect can be neglected for beam currents less than 300 nA. Thus, the ion losses of 3% at
this beam current range are related to the RF phase effect. With the existing devices, full ion beam can transmit to the RFQ once the RF phase effect is minimized. Unlike SHIRaC the losses still exist by minimizing this effect. This is caused by high RF amplitudes used in SHIRaC compared to those used in the existing devices which are less than 1 kV, table 2.

5.2 Simulation of cooling process

Once the ions are under the RFQ radial confinement and in presence of buffer gas they progressively undergo the cooling process. The simulation of this process has been performed by the Python program. Several parameters that may involve the cooling effects are evaluated in this program including the existence of buffer gas; the temperature of the ion trap; the inner radius of the quadrupole; the ion mass; the ion charge; the RF voltage and the q parameter.

In order to obtain optimum cooling, the space charge and the RF heating effects must be reduced. The first one can be minimized by increasing the RF amplitude while the second one can be reduced at low RF amplitude. For these reasons, the RF parameters should ensure that the Mathieu parameter \( q \leq 0.5 \). This condition limits the confinement capacity. Therefore, significant degradations of the cooling process by the second one can occur.

In this simulation both the space charge and the RF heating phenomena [48] are taken into account and the ion beam used is the one reaching the RFQ entrance.

Because the space charge increases progressively during this process, the reduction of the confinement capacity becomes significant, equation (2.3). Therefore, this effect will become an important factor for the ion losses, the degradation of the emittance and the spread energy.

The simulation results of the cooling process are illustrated on figure 6. The ion transmission (from the injection part entrance to the RFQ exit), the emittance \( \varepsilon_{60\text{keV}} \) and the spread energy \( \Delta E \) were investigated as a function of beam currents. The ion losses by the space charge can be seen in the decrease of the transmission: for intensities ranging from 100 nA up to 1 \( \mu \text{A} \), the transmission slightly falls by 15% (figure 6-left). However, more than 65% of ions can reach the exit of the RFQ even with a beam current of 1 \( \mu \text{A} \).
At the thermal equilibrium, the space charge increases the temperature of the cooled ions hence the increasing of the emittance [10, 11]. This effect is summed up on the figure 6-middle where the emittance increases slightly as a function of the beam current and it reaches around $1.25\,\pi\,\text{mm.mrad}$ for 1 $\mu$A beam current. This degradation is not important because the potential well depth $D$ is much higher than the space charge well depth $D_{SC}$ ($D\approx550\,\text{eV}$ and $D_{SC}\approx52\,\text{eV}$ for 1 $\mu$A beam with 1 eV of kinetic energy).

From figure 6-right, one can observe that the spread energy $\Delta E$ increases from 1.3 eV to 1.55 eV with beam currents going from 100 nA up to 1 $\mu$A. The space charge acts mainly on the transverse component of the ions' velocity. As spread energy stands for the spread of longitudinal component of the ions' velocity, and then this effect causes small degradations of $\Delta E$.

![Figure 6. Simulation of the space charge effects on the cooling process by Python programs: variation of the ion transmission (left), the emittance (middle) and the spread energy (right) as a function of beam current.](image)

### 5.3 Simulation of the extraction process

Following cooling and transmission through the RFQ, the cooled beam is extracted. Then it is guided with a small acceleration to the extraction plate exit. Once the beam passes through this plate it is strongly accelerated.

The most critical point in the acceleration of the beam is the area between the RFQ exit and the extraction plate exit, where the pressure of buffer gas is too high (close to the RFQ pressure). The problem unwinds in the absence of any confinement field. The good optical properties achieved by cooling the beam could be partially lost due to undesirable collisions of the extracted ions with the buffer gas atoms. In addition, the space charge will result significant degradations.

To evaluate these degradations, simulations were done by SIMION. Comparative simulation results of the beam parameters in addition to the transmission, at the RFQ exit and at the extraction part exit, versus the beam current depict these degradations, figure 7. Such degradations can be estimated by relying on the relative differences between the red curves (beam parameters and transmission at the exit of the RFQ) and the black curves (beam parameters and transmission at the exit of the extraction part). Those stemming from the buffer gas remain constant with the beam current and correspond to the gap between the curves at low beam current (less than 100 nA). These degradations revolve around the transmission, the emittance and more importantly the spread energy. They respectively reach 5%, 0.2 $\pi\,\text{mm.mrad}$ and 2.5 eV. The buffer gas diffusion is an engineering problem which can be solved by implementing a device providing both the transport of ions from one vacuum stage to another with only minor disturbances and confinement field. Due to the space
charge, this gap widens progressively with the beam currents. The spacing between the transmission simulation results, at the exit of the RFQ and after acceleration, is relatively constant with the beam current (figure 7-left). Thus, the space charge does not cause ion losses but only leads to a broadening of the ion beam size. This widening phenomenon contributes, with the space charge effects, to enlarge the emittance. The arising of these phenomena can be observed in the quick degradation of the emittance with the beam currents which increases from 1.15 to 2.4 $\pi \text{mm.mrad}$ for beam currents going from 100 nA to 1 $\mu$A (figure 7-middle). The spread energy is similarly affected and increases as a function of beam currents, figure 7-right.

Figure 7. Simulations of the extraction process by SIMION program: simulation results of the variation of the ion-transmission (left), the emittance (middle) and the spread energy (right) with beam current at the RFQ limit and at the extraction part exit.

5.4 Dependence of the cooling process on the ions mass

The SPIRAL 2 facility will produce radioactive isotopes ranging from the lightest to heaviest elements beyond uranium: a wide range of ion masses from 10 a.m.u up to 250 [5]. These ions could be handled by SIHReC.

The pseudo potential well dependence on the ion mass, equation (2.4), may affect the cooling process which becomes more degraded in the presence of space charge. At a given RF frequency $f$ and $q$ parameters the confinement potential well depth $D_{\text{max}}$ increases with the ion mass (equation (2.4)) unlike the well depth $D_{\text{SC}}$ which does not depend on it (equation (2.5)). For these reasons, the enhancing of cooling quality can occur when the ions mass increases. Therefore, both the beam parameters and the transmission improve for high ion mass.

Beyond the cooling part these cooled ions undergo degradations due to space charge and buffer gas pressure. These degradations are not related to the ion mass.

Table 1 compares the results obtained from the cooling simulations of ions with different masses and for 1 $\mu$A beam current. The transmission and the beam parameters for three ion mass levels: heavy mass ($^{133}\text{Cs}^+$ ions), medium mass ($^{87}\text{Rb}^+$ ions) and light mass ($^{23}\text{Na}^+$ ions), are presented. The results confirm the cooling dependencies on the ion mass. The lower transmissions and the higher beam parameters for the lighter masses, are due to RF heating [48]. This might explain the sharp degradation of the spread energy in the case of $\text{Na}^+$ ions relative to other ions.

The simulations reveal that in spite of all the degrading effects, which have been taking place along the RFQC beam line, the results obtained fulfill the HRS requirements for the transmission and the emittance. Only the spread energy is far from the HRS requirement.
Table 1. The cooling dependencies on the ions mass: ion-transmission and beam parameters of 1 µA ion beam at the exit of the extraction part.

| Ion mass | $^{133}$Cs$^+$ | $^{87}$Rb$^+$ | $^{23}$Na$^+$ |
|----------|----------------|--------------|--------------|
| $D_{\text{max}}$ (eV) | 552 | 361 | 95 |
| Transmission % | 65 | 49 | 25 |
| $\Delta E$ (eV) | 5.9 | 6.1 | 7.7 |
| $\epsilon_{60\text{keV}}$ ($\pi$.mm.mrad) | 2.4 | 2.7 | 3.5 |

6 Discussions and outlook

In this study we have dealt with the contributions of several phenomena such as space charge, RF phase, RF heating and buffer gas diffusion to degrade the cooling of beams with currents going up to 1 µA. We have shown that the RF phase and the RF heating phenomena are well minimized respectively at the entrance of the RFQ and along the cooling part. We have similarly shown that to overcome the space charge effects, occurring during the cooling process, only few kilovolts of RF amplitude are sufficient. However, the influences of space charge and buffer gas diffusion have adverse consequences at the RFQ exit.

According to these simulations, the transmissions efficiency of SHIRaC holds up the HRS requirements and they are in the same level of those obtained with existing devices despite the presence of the inherent space charge effects. This proves the efficiency of the optics system, the design and the appropriate selection of running parameters (the RF parameters and the voltages of electrodes).

The quality of the cooled beams obtained at the RFQ limit fulfill the project specifications for both the emittance and spread energy with the beam currents going up to 1 µA. Beyond the RFQ limit, such beam quality are degraded by the space charge and buffer gas. Regardless, the emittance remains close to the needed values. However, the spread energy becomes far from project specifications.

The performances of SHIRaC relative to the existing devices prevail in the handling of typical SPIRAL 2 beams as well as in the good cooling results of beams with low and high intensities.

At low beam currents (less than 200 nA), according to simulation results obtained at the exit of the extraction part, the spread energy and the transmission provided by SHIRaC are at the same level as those obtained with the present RFQCs. However, the beam quality seems better with SHIRaC because the emittance is only of $1 \pi$.mm.mrad compared to $2 \pi$.mm.mrad provided by the existing ones. The existing devices which provide the optimum results are JYFLTrap at IGISOL [15, 49–51], ISCoOL at ISOLDE [46, 47] and LEBIT at NSCL [14, 52–54], table 2. The optimum cooling provided by SHIRaC highlight the efficiency of large RF frequency to reduce the RF heating. Intuitively, they accomplish the HRS requirements.

When the beam current increases, both the beam parameters and the transmission are progressively degraded by the space charge. The emittance and the transmission still remain comparable to the optimum results provided by the existing devices. This explains the efficiency of the large RF
frequency to reduce the RF heating and the capacity of the high confining RF amplitude to overcome the space charge effects. However, the spread energy is strongly increased and exceeds the maximum of spread energy provided by present devices (5 eV), which was provided by the MAFF RFQC at Funnel project [13]. Subsequently, the optimum running of HRS becomes more difficult.

Table 2. Example of RFQC devices: summary of running parameters and results of the beam parameters and the ion-transmission.

| RFQC project          | Current (nA) | $V_{RF}$ (V) | $f_{RF}$ (MHz) | Pressure (Pa) | Transmission (%) | $\epsilon_{60keV}$ ($\pi$.mm.mrad) | $\Delta E$ (eV) |
|-----------------------|--------------|--------------|----------------|---------------|-----------------|-------------------------------|----------------|
| JYFLTrap (IGISOL)    | 5            | 300          | < 0.8          | 10            | 60              | 3                             | < 4            |
| ISCool (Isolde)      | 100          | 450          | 1.3            | 10            | 80              | 2.2                           | 4              |
| LEBIT (NSCL)         | 10           | 1000         | 1.15           | 10            | 70              | 3.3                           | 4              |
| SHIRaC (DESIR)       | 100          | 2800         | 4.5            | 2.5           | 82              | 1.2                           | 4              |
|                       | 1000         |              |                | 67            |                 |                               |                |

Our present design holds advantages for the injection part to capture more than 93% of incoming ions and the cooling part to gently improve the ion beam emittance. Albeit, simulated spread energy is not in agreement with the project requirements. As cited above, the degrading of spread energy is owing to the space charge and the diffusion of the buffer gas. Furthermore, another effect, never studied, can contribute to this degradation. It consists in the derivative of confining RF field at the exit of RFQ. The purely radial RF field can induce a longitudinal field at this region which acts on the longitudinal component of the ion beam velocity. It therefore acts on the spread energy. We should rather develop the extraction part, aiming for lower spread energy closer to 1 eV. One of the options under investigation is to set up a miniature RFQ at the exit of the RFQ part. This ingenious solution has been implemented in several RFQC projects [16, 52]. In the case of SHIRaC, the miniature RFQ should be able to reduce both the buffer gas diffusion and space charge effects.

7 Conclusion

Simulations show the efficiency of the optics of SHIRaC and the high RF parameters to handle beams of intensities never handled so far. The SHIRaC prototype achieves transmissions over 65% and emittances less than 3 $\pi$.mm.mrad. However, the validation of this project would require the experimental test of such device and the measurements of the emittance, spread energy and the transmission. Nevertheless these studies will be presented in next papers.

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References

[1] The DESIR facility, Letter of intents for SPIRAL 2 (2006).
[2] M. Lewitowicz, The SPIRAL 2 Project, Nucl. Phys. A 805 (2008) 519.
[3] Letter of intent for SPIRAL 2.
[4] S. Gales, SPIRAL 2 at GANIL: Next generation of ISOL Facility for Intense Secondary Radioactive Ion Beams, Nucl. Phys. A 834 (2010) 717.
[5] B. Blanc et al., DESIR: The SPIRAL2 Low-Energy Beam Facility, Technical Proposal for SPIRAL2 Instrumentation (2008).
[6] E.M. Ramirez et al., The ion circus: A novel circular Paul trap to resolve isobaric contamination, Nucl. Instrum. Meth. B 266 (2008) 4460.
[7] D. Toprek et al., DESIR high resolution separator at GANIL (France), Nucl. Tech. Rad. 27 (2012) 346.
[8] T. Kurtukian-Nieto et al., SPIRAL2/DESIR high resolution mass separator, Nucl. Instrum. Meth. B 317 (2013) 284.
[9] H. Franberg et al., Off-line commissioning of the ISOLDE cooler, Nucl. Instrum. Meth. Res. B 266 (2008) 4502.
[10] M.D. Lunney et al., Cooling of mass-separated beams using a radiofrequency quadrupole ion guide, Int. J. Mass Spectrom. 190/191 (1999) 153.
[11] T. Kim, Buffer gas cooling of ions in a radiofrequency quadrupole ion guide: a study of the cooling process and cooled beam properties, Ph.D. Thesis, McGill University, Montréal Canada (1997).
[12] W. Paul, Electromagnetic traps for charged and neutral particles, Rev. Mod. Phys. 62 (1990) 531.
[13] J. Szerypo et al., MAFFTRAP: ion trap system for MAFF, Nucl. Instrum. Meth. B 204 (2003) 512.
[14] G. Bollen et al., Penning trap mass measurements on rare isotopesstatus and new developments, J. Phys. B 36 (2003) 941.
[15] A. Nieminen et al., On-Line Ion Cooling and Bunching for Collinear Laser Spectroscopy, Phys. Rev. Lett. 88 (2002) 094801.
[16] F. Herfurth et al., A linear radiofrequency ion trap for accumulation, bunching, and emittance improvement of radioactive ion beams, Nucl. Instrum. Meth. A 469 (2001) 254.
[17] E. Mathieu, Mémoire sur le Mouvement Vibratoire d’une Membrane de Forme Elliptique, J. Math. Pures Appliqués 13 (1868) 137.
[18] R.B. Moore et al., Improving isotope separator performance by beam cooling, Nucl. Instrum. Meth. B 204 (2003) 557.
[19] A.D. Appelhans et al., SIMION ion optics simulations at atmospheric pressure, Int. J. Mass Spectrom. 244 (2005) 1.
[20] D.A. Dahl, Simion for the personal computer in reflection, Int. J. Mass Spectrom. 200 (2000) 3.
[21] D.A. Dah, Simion 3D V8.0 User Manual, Idaho National Engineering Laboratory, Idaho Falls U.S.A. (2000).
[22] F.H. Read et al., The charge-tube method for space-charge in beams, SPIE 3777 (1999) 184.
[23] G. Marx et al., HITRAP: A Facility for Experiments with Trapped Highly Charged Ions, Hyp. Int. 132 (2001) 463.

[24] E.P. Gilson et al., Use of a Linear Paul Trap to Study Random Noise-Induced Beam Degradation in High-Intensity Accelerators, Phys. Rev. Lett. 102 (2009) 145003.

[25] E.P. Gilson et al., Paul Trap Simulator Experiment to Model Intense-Beam Propagation in Alternating-Gradient Transport Systems, Phys. Rev. Lett. 92 (2004) 155002.

[26] H. Dehmelt, The Temperature of Buffer-gas Colled Ions in a Paul Trap, Adv. At. Mol. Phys. 3 (1967) 53.

[27] J. Neumayr, The buffer-gas cell and the extraction RFQ for SHIPTRAP, Ph.D. Thesis, Munchen University, Munchen Germany (2004).

[28] S. Henry, Piégeage et refroidissement d’ions exotiques pour la mesure de masse, Ph.D. Thesis, Louis Pasteur University, Strasbourg France (2001).

[29] P.H. Dawson, Quadrupole Mass spectrometry and its applications, Amer. Vac. Soc. Classics (1995).

[30] P.K. Ghosh, Ion traps, Clarence Press, Oxford U.K. (1995).

[31] M.D.N. Lunney et al., The Temperature of Buffer-gas Colled Ions in a Paul Trap, J. Mod. Opt. 39 (1992) 349.

[32] M. Petersson, Quadrupole Mass spectrometry and its applications, MSc Thesis, Linköping University, Linköping Sweden (2002).

[33] D. Rodriguez, A radiofrequency quadrupole buncher for accumulation and cooling of heavy radionuclides at SHIPTRAP and high precision mass measurements of unstable krypton isotopes at ISOLTRAP, Ph.D. Thesis, Universidad de Valencia, Valencia Spain (2003).

[34] A. Jokinen et al., RFQ-cooler for low-energy radioactive ions at ISOLDE, Nucl. Instrum. Meth. B 204 (2003) 86.

[35] F. Herfurth, Segmented linear RFQ traps for nuclear physics, Nucl. Instrum. Meth. B 204 (2003) 587.

[36] I. Podadera, Design of a second generation RFQ Ion Cooler and Buncher (RFQCB) for ISOLDE, Nucl. Phys. A 746 (2004) 647.

[37] D. Manura, Additional Notes on the SIMION HS1 Collision Model (2007), Scientific Intrument Services.

[38] S. Schwarz, IonCool — A versatile code to characterize gas-filled ion bunchers and coolers (not only) for nuclear physics applications, Nucl. Instrum. Meth. A 566 (2006) 233.

[39] Private communication, Simulation working group meeting report (Ion catcher, NIPNET, HITRAP), University of Munich (LMU), Munich Germany, 27–28 September 2002.

[40] A. Appelhans et al., Measurement of external ion injection and trapping efficiency in the ion trap mass spectrometer and comparison with a predictive model, Int. J. Mass Spectrom. 216 (2002) 269.

[41] M.W. Forbes et al., Simulation of ion trajectories in a quadrupole ion trap: a comparison of three simulation programs, J. Mass Spectrom. 34 (1999) 1219.

[42] A. Viehland et al., Tables of transport collision integrals for (n,6,4) ion-neutral potentials, At. Data Nucl. Data Tables 16 (1975) 495.

[43] H.W. Ellis et al., Transport properties of gaseous ions over a wide energy range. Part II, At. Data Nucl. Data Tables 22 (1978) 179.
[44] S. Schwarz, Simulations for Ion Traps Buffer Gas Cooling, Lecture Notes Phys. 749 (2008) 1.

[45] V.S. Rudnev, Electronic spectroscopy of cold ions in a radio-frequency trap, Ph.D. Thesis, University of Basel, Basel Switzerland (2010).

[46] I. Podadera et al., Preparation of cooled and bunched ion beams at ISOLDE-CERN, Eur. Phys. J. A 25 (2006) 743.

[47] I. Podadera, New developments on preparation of cooled and bunched radioactive ion beams at ISOL-facilities: the ISCOLL project and the rotating wall cooling, Ph.D. Thesis, Universitat Politècnica de Catalunya, Barcelona Spain (2006).

[48] F.G. Major et al., Exchange-Collision Technique for the rf Spectroscopy of Stored Ions, Phys. Rev. 170 (1968) 91.

[49] P. Karvonen et al., A sextupole ion beam guide to improve the efficiency and beam quality at IGISOL, Nucl. Instrum. Meth. B 266 (2008) 4794.

[50] A. Nieminen et al., Beam cooler for low-energy radioactive ions, Nucl. Instrum. Meth. A 469 (2001) 244.

[51] A. Jokinen et al., The first cooled beams from JYFL ion cooler and trap project, Nucl. Phys. A 701 (2002) 557.

[52] S. Schwarz et al., A second-generation ion beam buncher and cooler, Nucl. Instrum. Meth. B 204 (2003) 474.

[53] T. Sun et al., Commissioning of the ion beam bender and cooler for LEBIT, Eur. Phys. J. A 25 (2006) 61.

[54] T. Sun, High precision mass measurement of $^{37}$Ca and developments for LEBIT, Ph.D. Thesis, Michigan States University, East Lansing U.S.A. (2006).