PROGRESS ON THE RFQ BEAM COOLER DESIGN FOR SPES PROJECT

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Abstract

The SPES project is the new Radioactive Ion Beam facility under construction at Laboratori Nazionali of Legnaro, Italy. In this framework, a study of a new RFQ beam cooler device is in progress in order to improve the beam quality in terms of transverse emittance and energy spread. The electromagnetic design of the RFQ section and the electrostatic layout of the injection and extraction regions have been done. The beam dynamics study is going on by means of dedicated codes which allow to take into account the interaction of the ions with the buffer gas needed to cool the beams. The preliminary design of the device started in 2011 by V Committee of INFN in the framework of the REGATA experiment. Both beam dynamics study and the electromagnetic design are presented in this work together with the experimental set up to investigate the sustainability of high voltages at low He pressure.

INTRODUCTION

The experiments with radioactive beams require beams of high purity while the methodology ISOL (Isotope Separator On Line), used to produce them is isotopically unselective. Actually the output beam from the first mass selection (resolution 1/200) is constituted by all the radioisotopes with charge +1 and with almost the same mass number. In order to separate the radioisotope of interest from the contaminants, which may have intensities orders of magnitude higher a further mass selection, is required. This mass selection is carried out by High Resolution Mass Spectrometers (HRMS) whose capacity of selection (1/20000), without loss of transmission, depends on the emittance of the incoming beam. A lower emittance has the further advantage of reducing the beam transport losses and, moreover, makes easier the detection of radioisotopes and increases the accuracy of the measurement of their properties.

The devices used to reduce the emittance of low energy (a few tens of keV) radioactive beams are called buffer gas-filled Radio Frequency Quadrupoles (RFQ) cooler [1]. Many devices of this type have been successfully used up to now to reduce the beam emittance of low current (a few pnA) ion beams. However, the increased beam current intensity (up to 1μA) of the new generation ISOL facilities such as for example SPIRAL2, asks for new technological challenges for their fulfilment [2,3].

BEAM COOLER CONCEPT

In a RFQ cooler, a quadrupolar electric field, generated by two pairs of electrodes placed at distance $2r_o$, oscillating in phase opposition at frequency $\omega/2\pi$ and at amplitude voltage V_{rf} , provides a potential well which can confine the motion of a particle of charge *e* and mass *m*. It can be shown that the particle motion is stable when the Mathieu parameter *q*, given by:

$$q = \frac{4eV_{rf}}{m\omega^2 r_0^2} \qquad (1)$$

satisfies the conditions $0< q<1$.

For *q* values within this range, the particle motion in the quadrupole is, in first approximation, the sum of two predominant motions, the micromotion, which is the particle oscillation at the frequency of applied electric field, and the macromotion, which is due to the effect of the potential well created by the quadrupolar RF field configuration. The micromotion amplitude is attenuated approaching the axis of the quadrupole, according to the decrease of the electric field. It is then amplified when the ion moves away from the axis. This type of motion is always revitalized by the electric field applied to the electrodes.

As a first approximation (for values of *q* less than 0.5), the frequency of the macromotion is related to that of the micromotion by the relation

$$\omega_M = \frac{q}{2\sqrt{2}}\omega \qquad (2)$$

It may likewise be shown that, the amplitude of the macromotion oscillation exceeds of a factor *2/q* the maximum micromotion amplitude. The ion then performs a wide oscillations at macromotion frequency, that are perturbed by micromotion. The amplitude of the macromotion movement is reduced in presence of dissipative processes, as collision with gas molecules present in the RFQ structure. The ion exchanges part of its energy with the gas molecule in the impact. It can be shown that, in average, the ion loses energy only if the gas molecule has an atomic weight lower than the ion ones [4]. It is also important that the buffer gas is neutral and inert in order to not remove beam ions by chemical reactions or charge exchange processes. The energy loss increases with the number of collisions, which is proportional to gas pressure. A gas inlet in the structure makes the process more efficient. The overall effect of the collisions is to introduce a viscous force which slows the ion until it reaches a constant drift speed. The introduction of this force in the equation of motion reduces the amplitude and lowers the frequency of the macromotion oscillation. The effect of the gas is therefore to reduce both transverse size and speed of the beam so to decrease its transverse emittance.

The component of the viscous force along the axis of the structure also produces a decrease in the longitudinal component of the ion speed and then lowers, together with it, also the energy spread.

To guide the beam to the exit and, if required, to allow beam bunching, a longitudinal electric field is created. The beam cooling can be carried out only when the incoming beam energy is sufficiently low to allow both the beam trapping in the potential well created by the RF field and a sufficient number of interactions between the beam ions and the buffer gas. For this reason an RFQ cooler for an ISOL facility foresees an entrance section for beam deceleration down to energy of about 100-200eV, limit given by the necessity to penetrate the potential well. An exit section makes the beam to recover the original energy.

High buffer gas pressure (up to few Pa) in the quadrupole makes the beam dumping faster but, in order not to lose beam intensity, high vacuum conditions have instead to be assured at quadrupole injection and extraction sections. Therefore, it is mandatory to maintain high differential vacuum conditions between the three cooler sections. At high beam intensities, high RF voltage amplitude (up to some kV) and, related by the *q* formula, also high frequencies (tens of MHz), are required in order to compensate for the sparce charge effects.

An R&D program is going on in parallel with the preliminary RFQ cooler electromagnetic and electrodynamics design in the frame of the INFN-CNV experiment REGATA.

REQUIREMENTS FOR THE SPES BEAM COOLER

SPES is an ISOL radioactive beam facility under construction at LNL [5]. The radioactive beam produced by the target station [6] can be re-accelerated by ALPI, the superconducting linac for heavy ions in operation at LNL, to reach an energy exceeding 10 MeV/A. SPES production facility foresees a cyclotron accelerating a primary beam consisting of 700 µA of protons up to 70 MeV.

The impingement of the primary beam on the original production UCx target, developed at LNL, provides radioactive ions with a current intensity up to 2 µA in the mass range of 9-160 AMU. The target station is placed on a 40 kV platform.

A Wien Filter located downstream the source makes a first stage mass selection and reduces the beam intensity to about 50 nA. The ion beam is then delivered through the transport line with a geometric emittance of 30 π mm mrad at 40 kV. To achieve the resolving power higher than 1/20000 for the HRMS, the Cooler device, placed upstream the mass selection, has to reduce the transverse beam emittance of about a factor 8. Once the beam is selected in mass, it is injected into the Charge Breeder (CB) [7] based on a ECRIS design, in order to lower the mass to charge ratio down to A/Q≤7. To get the maximum injection efficiency of the CB, it is crucial to keep below some eV the energy spread of the ion beam.

The main goal of a Beam Cooler is therefore both to reduce the transverse emittance of the radioactive ion beam by a factor 8 and to maintain low the longitudinal emittance providing an energy spread of the cooled beams to about 1eV.

PRELIMINARY COOLER DESIGN

The RFQ beam cooler device is composed by 3 main sections: the deceleration system, which lowers the energy of the incoming beam from 40 keV down to some hundreds of eV; the confinement and cooling section which consists of the RFQ device and the main vacuum vessel placed on a 40 kV high voltage platform; finally the acceleration section where the cooled beam is extracted and achieves the initial energy of 40 keV. The buffer gas is injected in the cooling section in order to reach a pressure within 0.5÷3 Pa

The energy of the reference beam was decreased in respect of the previous calculation [8] in order to make easy the RFQ accelerator design expected for SPES [9].

The electromagnetic field configuration was studied by the use of 3D FEM code OPERA, whereas the beam dynamic was analyzed by the dedicated code SIMION ver 8 in order to take into account the collisional effects with the buffer gas molecules for simulating the cooling process. In this preliminary design phase, we neglected the space charge effects on the beam transport since the current of the Radioactive Ion Beams is lower than 100 nA.

Table 1 sums up the main parameters of the device.

Table 1: Design parameters of a beam cooler for SPES

Parameter	**Value**
Mass Range	9-200 AMU
Buffer Gas	He @ 293 K
Transverse Emittance injected beam	30 π mm mrad @ 40 keV (Q=1+)
Beam current	50-100 nA (10^{11} pps)
Emittance reduction factor	10 (max)
Energy Spread	< 5 eV
RF frequency range	1-30 MHz
RF Voltage range	0.5-2.5 kV
RFQ gap radius (r_o)	4 mm
RFQ total length	700 mm
Pressure Buffer Gas	0.1 – 2.5 Pa
Ion energy at cooling	100 – 200 eV

Injection and Extraction Sections

SPES target station delivers radioactive beams with charge Q=1+ and energy of 40 keV at the entrance of the RFQ Beam Cooler device**.** A system of four electrostatic lens decelerates the beam to 200 eV before the RFQ cooling section. The lens array gradually decelerates the ion beams to low energy, thus avoiding strong ion-optical effect that leads to harmful beam losses during the injection into the collisional ion guide.

The conical shape of the two mid stage electrodes allows beam focusing and compensates the natural diverging effect due to the deceleration process. We chose such electrode configuration in order to achieve the 100% transmission efficiency between the injection and the RFQ sections.

Figure 1 shows a sample plot of the trajectories of Cs 1+ ion through the electrode system. As shown, all of the ions are focused into the RFQ through the 6 mm diameter entrance aperture.

Following the cooling process through the RFQ, the ion beams exit through a 6 mm diameter aperture and then they recovered the initial energy by a two electrode stages.

Confinement and Cooling Section

The RF quadrupole consists of four cylindrical rods of 9 mm of diameter. The distance between the opposite pair of rods is $2r_o$=8 mm The rods are 700 mm length and they are divided into 10 segments of 69.5 mm each.

The segmentation allows to produce 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 applied RF voltage and the operating frequency depends on the ion mass delivered which varies within 9-200 AMU and on the current intensity of the incoming beam. Table 1 shows the ranges of the different parameters.

He at 293 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 and on the RF voltage applied to the quadrupole.

By the preliminary results given by the SIMION code using the hard sphere model to calculate the interaction gas-ion, we simulated the cooling process and we achieved a transverse emittance reduction of a factor 8-10.

The differential pumping system is very crucial for obtaining optimal cooling and transmission efficiency.

The gas leakage through the entrance apertures causes the energy degradation of the beam and the related beam losses due to the scattering with molecules of the residual gas. These harmful effect can be reduced by both the careful design of the differential pumping system and the optimization of the design of the injection and extraction electrodes and their placing with respect to the entrance and exit of the vacuum chamber where the RFQ is placed.

This design is under study in collaboration with the CERN team.

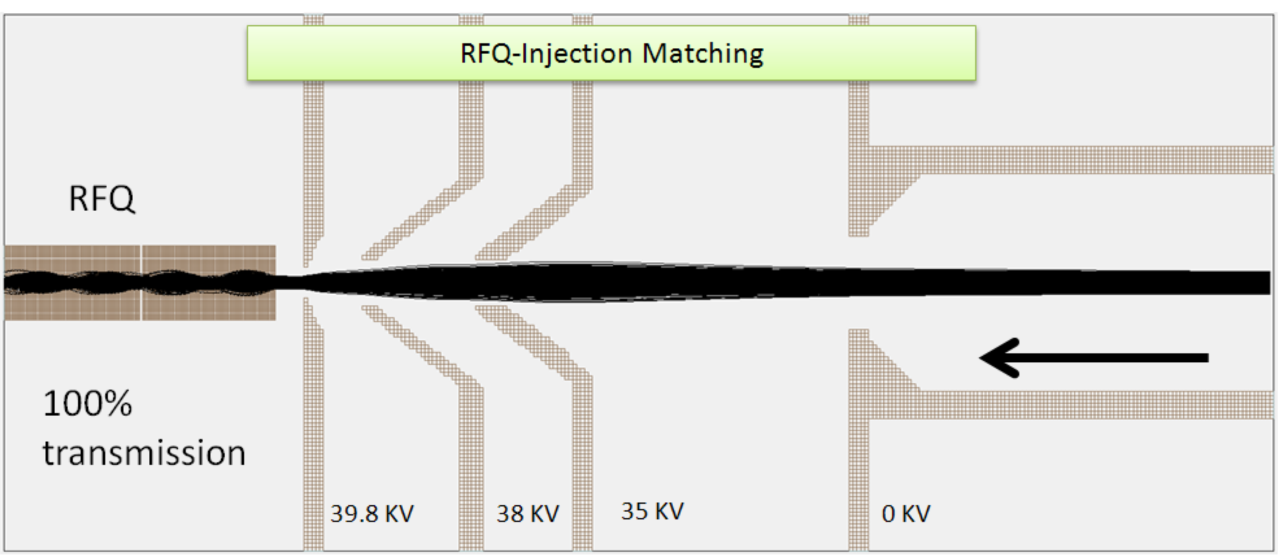

Figure 1: The SIMION beam transport simulation for the $^{133}Cs^{1+}$ beam along the deceleration system. This is composed by 4 stage of electrodes at different voltage. As shown the waist is placed as close as possible to the RFQ entrance in order to fully match the related acceptance.

APPARATUS FOR DISCHARGE DETECTING

Despite the expected radioactive ion beam intensity for SPES (50 nA) is lower than ones reachable in the facility SPIRAL 2, however it is anyway much higher than other coolers in operation.

As described in the previous paragraph, a high current cooler requires to apply an RF voltage of some kV to the electrodes in presence of a buffer gas at pressure of some Pa.

This pressure range is near to the minimum of the Paschen curve [10], showing the discharge voltage as a function of the product between pressure and electrode distance, as a consequence electrical discharge can be an issue for the beam cooler operation. For this reason we foresaw, in the frame of the experiment REGATA, the construction of an experimental set up aimed at studying experimentally study the conditions at which the discharges between the electrodes may occur. In such apparatus we can assemble electrodes of different shape and automatically vary their distance without the necessity of opening the vacuum chamber. In addition we can easily change the applied (DC) voltage or Helium pressure level. In such way we can evaluate the dependence of the discharge offset from such parameters and, moreover, the influence of shape and surface preparation of electrodes.

The test apparatus includes a CF150 flange (fig 2) which holds the two electrodes.

One of the electrode, supported by PEEK made insulators is connected by an high voltage feed-through to a high voltage power supply.

A linear actuator allows to change the position of the second electrode, maintained at ground potential. The assembling system is designed in order to make an easy exchange and alignment of the electrodes.

The CF flange has apertures for the pressure gauge and gas inlet and will be integrated in an existing high vacuum apparatus. Figure 3 presents the working scheme of the test discharge apparatus and of its control system.

A 10 kV programmable power supply creates the voltage ramps. Both a four channel oscilloscope and an universal USB Card allow the acquisition of possible current spikes and of their dynamic behavior.

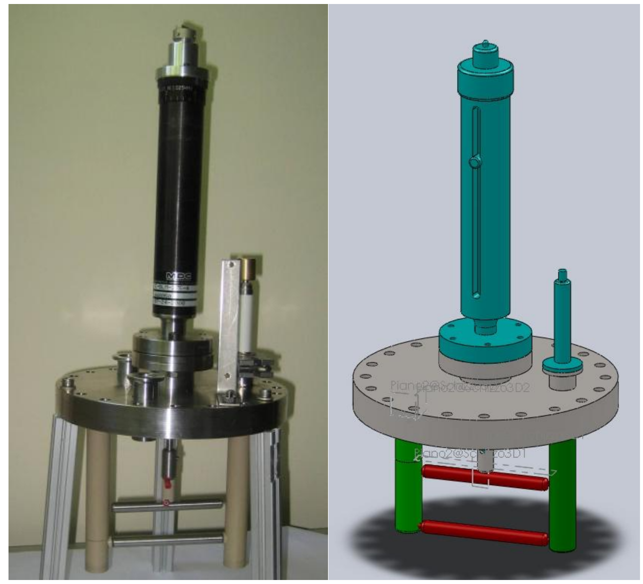

Figure 2: Drawing of the pressure test system and top flange of the apparatus under construction for testing conditions of discharges at low He pressures.

The USB card also controls the HV power supply and gas flow equipment. A computer controlled stepping motor moves the electrodes by a linear feed-trough.

All the data are gathered and visualized by a PC controlling both electrode movement and test operation sequence.

CONCLUSION

The design of the RFQ beam cooler for SPES project started in 2011

This report presents the results of the electromagnetic layout and the first analysis of the beam dynamics

We chose the operational parameters of the device and we are now carrying on the process of optimization of the structure. Once this first phase of study is accomplished out, we will complete the beam dynamics analysis by the introduction of the space charge effects.

An experimental set up for testing the sustainability of the high voltage necessary to the cooler operation is now ready for measurements.

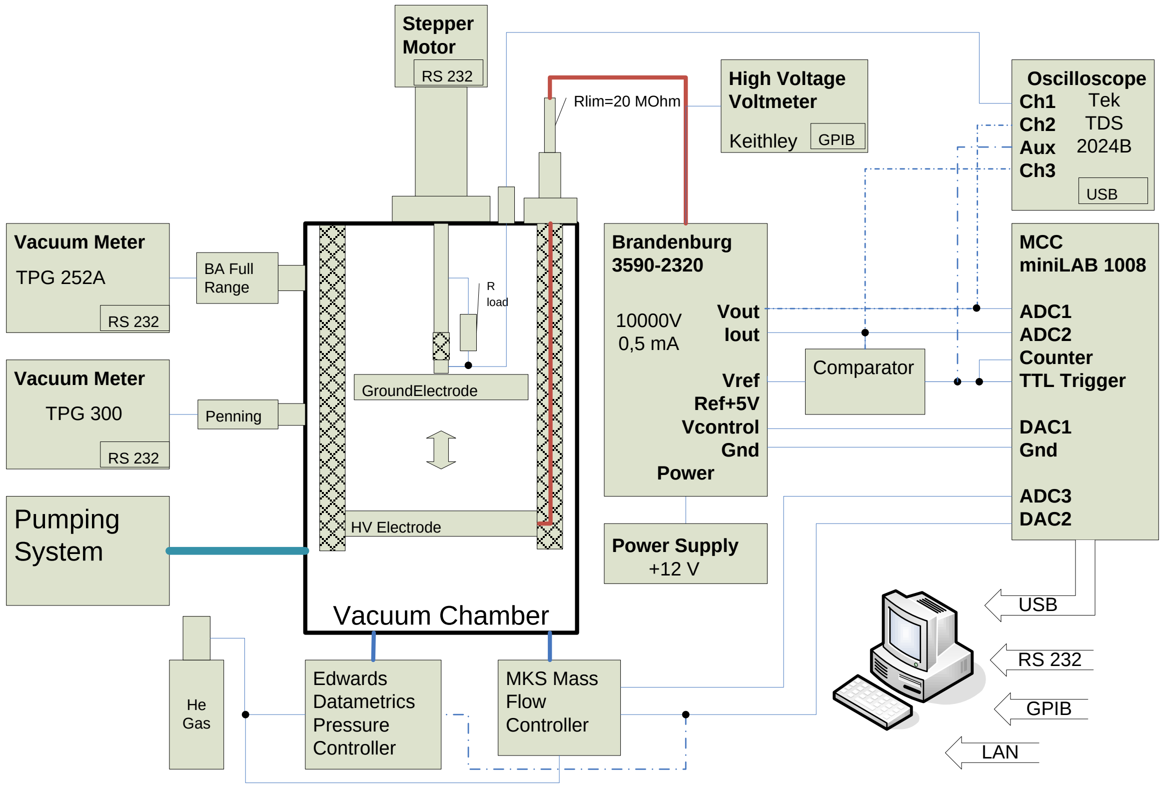

Figure 3: Working scheme of the test set up for detecting discharges at low gas pressure.

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