Radio Frequency Quadrupole Cooler and Buncher Model and Simulation for CERN-ISOLDE at Offline 2

Jara Wilensky, CERN, Geneva, Switzerland
Supervisor: Dr. Maximilian Schuett

Abstract

The RFQcb at Offline 2 is a replica of ISCOOL at the ISOLDE facility. An RFQcb improves beam quality and decelerates the ion beam for storage, and later, extraction in bunches. Previously, the ion beam in an RF field and the ion-gas collisions were simulated separately as the software used for the modeling and simulations was unable to simulate both aspects of the RFQcb together. A complete simulation required the use of a new software, SIMION Ion and Electron Optics Simulator. The new model in SIMION has been completed and we have begun simulating the complete RFQcb with various trapping potentials and buffer gas pressures. Both trapping and transmission of the ions has been achieved by changing the potential of axial electrodes along the RFQcb.

Geneva, Switzerland
August 18, 2023

1 Introduction

The radio frequency quadrupole cooler and buncher (RFQcb) at Offline 2 is a replica of the RFQcb, ISCOOL, at the ISOLDE facility. ISOLDE, the Isotope Separator On-Line DEvice, is an on-line fixed-target facility which receives approximately 50% of the proton beam from the Proton Synchotron Booster. In order to more efficiently use beam time and ensure quality control, Offline 2 was constructed as a non-radioactive equivalent testing environment for the Front End and RFQcb before upgrades are installed at ISOLDE.[1]

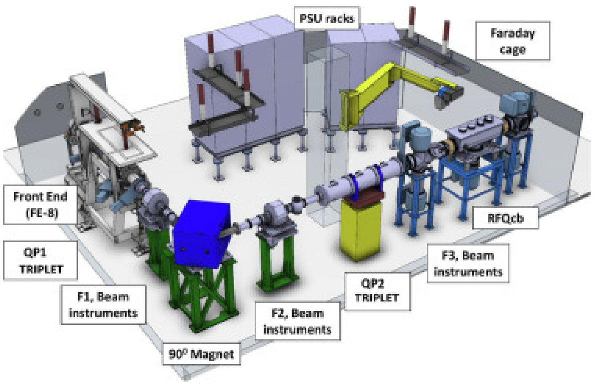


Figure 1: Schematic of Offline 2 beamline. The Front End is the ion source and the RFQcb is directly before the target.[2]

1.1 RFQcb at Offline 2

An RFQcb improves beam quality and decelerates the ion beam for storage, and later, extraction, in bunches. The radio frequency quadrupole improves beam quality by applying an alternating RF field to transverally confine and focus the ions.

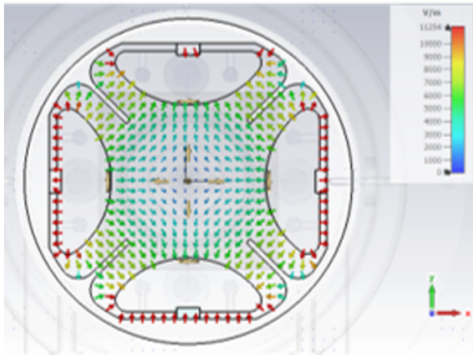


Figure 2: Cross-section of the electric fields in the transversal XY-plane showing the alternating quadrupole electric RF fields that keep the ions confined and focused.[3]

The quality is then further improved by the addition of a buffer gas, He. The transfer of momentum from the ion-gas collisions cools the ions, reducing the transverse emittance as the ions move along the RFQ. By adding a DC longitudinal potential ramp through a series of axial electrodes, the ions are decelerated until they reach the storage region, a potential well. The potential of the electrodes after the storage region can be changed to switch from bunching mode, for storage, to transmission mode, after which the ion bunches can be reaccelerated.[1]

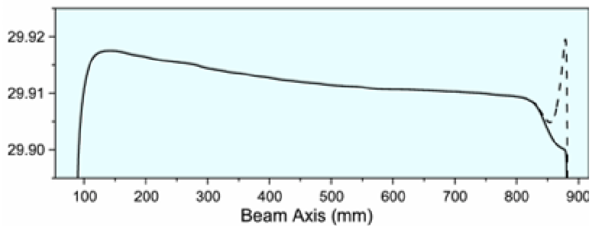


Figure 3: Longitudinal ramped DC potential (kV) along the RFQcb beam axis in transmission mode (solid) and bunching mode (dashed).[1]

The RFQcb at Offline 2 has additional features for the buffer gas pressure, RF system, and axial electrodes. It has double the pumping capacity as well as a greater range of operational gas pressures that can be dynamically controlled. The RF system's power is greater by a factor of ten and has a greater frequency range. Finally, the RFQcb can operate at the same beam energies, 30 keV to 60 keV, but with improved controls, allowing for greater tuning ability. [2]

1.2 Motivation

Previously, the ion beam in an RF field and the ion-gas collisions were simulated separately as the software used for modeling and simulations was unable to simulate both aspects of the RFQcb together. A complete simulation required the use of a new software, SIMION Ion and Electron Optics Simulator. SIMION is a particle field and trajectory simulator that calculates the EM fields in a defined area using voltages and particle definitions input by the user. This new software necessitated a new model and simulation built specifically for use in SIMION. The goal of my project was to build the model and begin simulations to better predict the effects of different buffer gas pressures, optimize timing for the extractions, and optimize the potentials for the longitudinal ramp.

2 The RFQcb Model

2.1 Building the Model in SIMION

Due to difficulties with SIMION Version 8.2.0.11, various methods were attempted to build the model. As the RFQcb was already modeled in CST Microwave Studio, the first method attempted was to import the geometry as an STL file directly from CST, then convert it to a potential array (PA) file using the included SL Tools program.

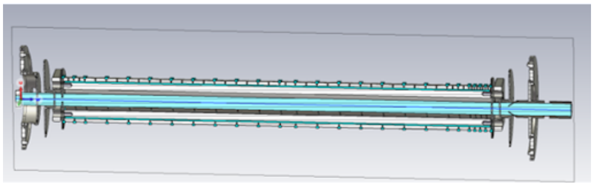


Figure 4: RFQcb as modeled in CST Microwave Studio.

A recent software update allowed for a GEM file to be simultaneously made while converting the STL file, theoretically allowing individual imports of each part, before combining them into one GEM file. However, this method was unsuccessful due to a malfunction which caused the voltages of the electrodes to be unpredictably located in the geometry outside the defined shapes. We concluded that the issue lay in the STL file from CST, motivating a different approach.

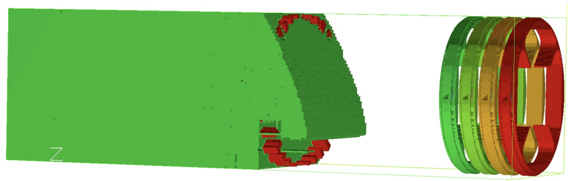


Figure 5: PA after importing the STL files from CST Studio using SL Tools. The block on the left was randomly placed and unable to be removed programmatically. The axial electrodes on the right are the intended geometry.

The next attempt was to use the AutoCAD Inventor model from which the CST model was derived, and then import the STL files directly into the GEM file. The same issue occurred with importing parts directly, so parts were built from scratch in Inventor, instead. For an unknow reason this method was only successful for the axial electrodes.

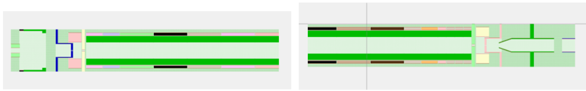
SIMION allows for users to create more complex geometries from scratch using GEM files which can be processed and edited using the "Modify" function. These text files use combined GEM and LUA syntax which is read by SIMION to define a PA. One advantage of this method is that the electrodes can be dynamically adjusted with a LUA file that is called by the SIMION workbench. This aspect is essential for the alternating RF field. Although more tedious, this ended up being the primary method for creating the model, with only the axial electrodes being imported as STL files.

2.2 The Model in SIMION

The final model was created with a GEM file defining the basic geometries of named electrodes within a PA, whose potentials could be programmatically changed both with a LUA file and within the SIMION workbench. Due to long compiling times, the file was divided into four parts: injection end, extraction end, axial electrodes, and quadrupole.

Figure 6: 3D view of the RFQcb modeled in SIMION. A change in color refers to a change in potential.

Dividing the geometry into four parts and defining the potentials with the user programming option decreased the file size from 7 GB to 200 MB and decreased the compiling time by a factor of 10. The time and size could be further decreased by defining the axial electrode geometry in the GEM file instead of importing them as an STL file.



(a) (b)

Figure 7: Cross-sections of the injection (a) and extraction (b) electrodes in the YZ-plane of SIMION. The injection electrodes are used as an Einzel lens to focus the beam into the RF region. Ions are re-accelerated to their previous energy by extraction electrodes.

3 The RFQcb Simulation

3.1 Defining the Potentials

The initial potentials used for setting up the simulation were from RFQ simulations without the buffer gas. Once the GEM file is processed by SIMION, the file is converted into a solution file, refined, then loaded into the workbench. Within the workbench, the user can call a LUA file to adjust the potentials of the electrodes and define adjustable variables to be controlled from the "Variables" tab.

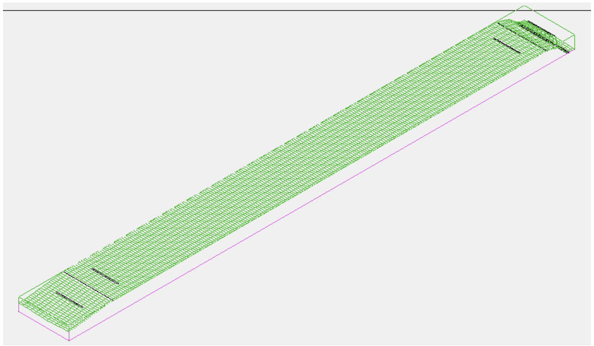


Figure 8: YZ cross-sectional potential energy plot in SIMION.

The entire RFQcb is raised to the platform potential, 30 kV, and then electrodes are slightly offset to produce the longitudinal DC potential ramp and control ion behavior at the injection and extraction ends. Switching between storage and transmission mode can be controlled directly in the LUA file or "Variables" tab.

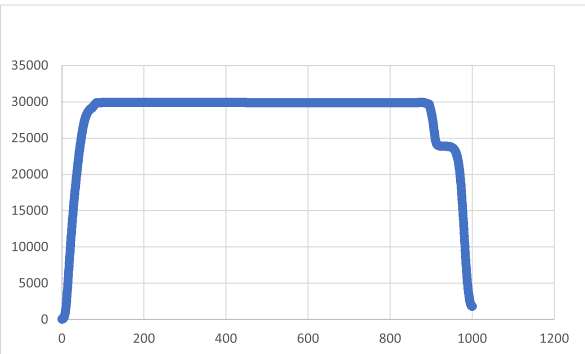


Figure 9: Longitudinal ramped DC potential (kV) along the RFQcb beam axis in transmission mode. This is the expected result and is the same as Fig. 3.

The alternating RF field is defined in the LUA file through the "fast_adjust" command. The equations defining the oscillations are given by

$$\text{adjust\_elect01} = V_{platform} + V_0 \sin \omega t$$

$$\text{adjust\_elect02} = V_{platform} - V_0 \sin \omega t$$

where electrode01 is one pair of opposite poles and electrode02 is the other pair, defined such that the force on the ions is always opposite between the pairs. The values of the parameters are adjusted depending on the ion source.

3.2 Defining the Particles

Particle defintions can be done both in the LUA file and using the "Define Particles" tab. The FLY2 type of definiton was used to define the ions as a group and allows for more flexibility than the FLY type. The definitions of ions can be easily changed to test different ion sources.

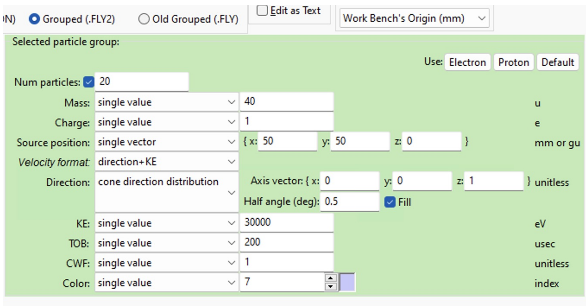


Figure 10: "Particles Defintion" tab in the SIMION workbench. Values are given for an ion beam of $^{40}Ar^{+}$. Some radial distribution of particles is expected and estimated as a cone.

3.3 Defining the Buffer Gas

My project partner, Mutua Onesmus John, was responsible for defining the buffer gas and led the incorporation of the buffer gas component into the simulation. The buffer gas component was imported into the main LUA file and uses a modified "Hard Sphere Collision" model. [4]

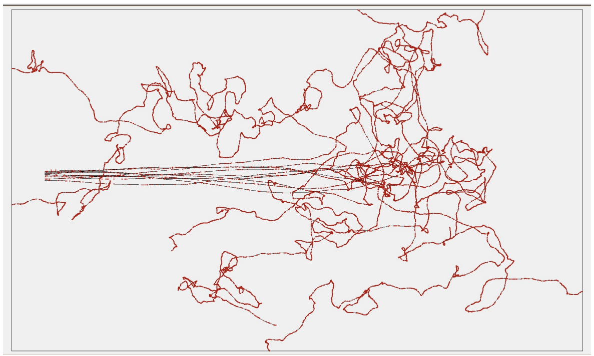


Figure 11: XY cross-sectional view of the "Hard Sphere Collision" model run in SIMION. Ions collide against background gas and are deflected randomly.

4 Results

The model has been completed and we have begun simulating the complete RFQcb in SIMION with various trapping potentials and buffer gas pressures. As expected, the result of adding the buffer gas is a visually improved beam path.

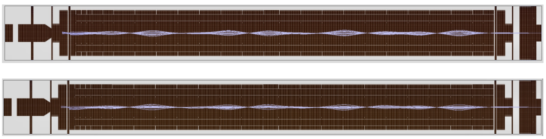


Figure 12: XZ cross-sectional view of 20 ions simulated in SIMION without the buffer gas (above) and with the buffer gas (below). Note the transversal confinement when the buffer gas is added and the ion trapping at the end of the RFQcb.

More ions are transversely confined and make it through the aperture into the extraction region when the buffer gas is added. This result could be visually confirmed due to the small amount of particles simulated per run. Both trapping and transmission of the ions has been achieved by changing the potential of axial electrodes along the RFQ. The location of trapping can also be adjusted programmatically.

5 Outlook

The simulation is running successfully and the next step is to write a script to process the recorded data efficiently. Once the code is written, greater amounts of ions will be simulated, and pressure, potential and extraction timing optimization will begin. Eventually, these values will be experimentally tested in Offline 2.

Acknowledgments

I would like to thank my supervisor, Dr. Maximilian Schuett, for guiding me through this project and introducing me to the topic of experimental accelerator physics. Thank you to my project partner, John, for his help with successfully building the simulation and the hours we spent with our supervisor brainstorming and troubleshooting. Thank you to the ISOLDE team for helping come up with solutions to improve my code and explaining the experiments and equipment. Lastly, I would like the thank the CERN Summer Student Programme and 2023 University of Michigan-CERN Research Experiences for Undergraduates for providing me with this opportunity and mentors to support me as I continue my physics education.

This material is based upon work supported by the National Science Foundation under Grant No. PHYS-2243608.

References

[1] M. Schuett, "Commissioning of the rfqcb at the isolde offline 2 target test facility," *IPAC'23-14th International Particle Accelerator Conference*, 2023.

[2] S. Warren, T. Giles, C. Pequeno, and A. Ringvall-Moberg, "Offline 2, isolde's target, laser and beams development facility," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 463, pp. 115–118, 2020.

[3] M. Schuett, "Rfq development at the cern-isolde offline 2 mass separator," September 2022.

[4] SIMION, "collision_hs1.lua," *SIMION Supplemental Documention*, 2021.