

**Ion Extraction and Identification from Gaseous
Xenon: A Commissioning Study for
Barium Tagging in nEXO**



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Abstract

One of the long-standing questions in physics is that of matter-antimatter asymmetry observed in the Universe. Neutrinos are excellent candidates for searching for new physics to explain this asymmetry through theories, such as leptogenesis, that require the violation of lepton number conservation. Neutrinoless double beta decay ($0\nu\beta\beta$) is a rare process that, if observed, would be the first evidence of lepton number violation and demonstrate the Majorana nature of neutrinos.

The nEXO experiment proposes the search for $0\nu\beta\beta$ in 5 tonnes of liquid xenon enriched to 90% in the double beta decaying ($2\nu\beta\beta$) isotope ^{136}Xe . The goal of nEXO is to probe the $0\nu\beta\beta$ half-life of ^{136}Xe with a sensitivity of up to 10^{28} years, two orders of magnitude above the current upper-limits in hope of discovery. To further enhance the discovery potential, a proposed future upgrade involving a technique referred to as barium tagging is being explored to extend the sensitivity of nEXO. This technique aims to extract and identify the $0\nu\beta\beta$ daughter ^{136}Ba as a means of active-background rejection against all gamma backgrounds. As part of the Ba-tagging scheme, we have developed a setup to study the extraction of ions from gaseous xenon. The setup combines a radio frequency (RF) funnel, a linear Paul

ion trap (LPT), and a multiple-reflection time- of-flight mass spectrometer (MRTOF-MS) to extract, trap, and perform mass spectrometry on ions, respectively. This thesis presents the commissioning of the RF funnel and LPT subsystems. Ion extraction from gaseous argon was used to study and validate the operation of the RF funnel in preparation for operation with gaseous xenon. In addition, results from the operation of the MRTOF-MS with bunched ions from the LPT are presented, demonstrating its readiness for future mass measurements. Overall, the results confirm that the setup is ready for operation and, once optimized, will enable benchmarking of the overall barium tagging efficiency.

Abrégé

L'une des questions fondamentales de la physique moderne concerne l'asymétrie matière-antimatière observée dans l'Univers. Les neutrinos constituent d'excellents candidats pour la recherche de nouvelle physique pouvant expliquer cette asymétrie à travers des théories, telles que la leptogenèse, qui nécessitent une violation de la conservation du nombre leptonique. La désintégration double bêta sans émission de neutrinos ($0\nu\beta\beta$) est un processus rare qui, s'il était observé, constituerait la première preuve d'une violation du nombre leptonique et démontrerait la nature Majorana des neutrinos.

L'expérience nEXO propose la recherche de la $0\nu\beta\beta$ dans 5 tonnes de xénon liquide enrichi à 90 % en isotope double bêta radioactif ($2\nu\beta\beta$) ^{136}Xe . L'objectif de nEXO est de sonder la demi-vie du $0\nu\beta\beta$ du ^{136}Xe avec une sensibilité pouvant atteindre 10^{28} années, soit deux ordres de grandeur au-delà des limites supérieures actuelles, dans l'espoir d'une découverte. Afin d'accroître davantage le potentiel de découverte, une amélioration future proposée, reposant sur une technique appelée identification du barium *barium tagging*, est actuellement à l'étude pour étendre la sensibilité de nEXO. Cette technique vise à extraire et identifier le noyau fils ^{136}Ba issu de la $0\nu\beta\beta$ comme moyen de rejet actif des bruits de fond

gamma. Dans le cadre du schéma de *Ba-tagging*, nous avons développé un dispositif destiné à étudier l'extraction d'ions à partir de xénon gazeux. Ce dispositif combine un entonnoir radiofréquence (RF funnel), un piège linéaire de Paul (LPT) et un spectromètre de masse à temps de vol à réflexions multiples (MRTOF-MS) afin d'extraire, de piéger et d'effectuer la spectrométrie de masse des ions, respectivement. Cette thèse présente la mise en service des sous-systèmes de l'entonnoir RF et du LPT. L'extraction d'ions à partir d'argon gazeux a été utilisée afin d'étudier et de valider le fonctionnement de l'entonnoir RF en préparation de son utilisation avec du xénon gazeux. De plus, les résultats de l'exploitation du MRTOF-MS avec des paquets d'ions provenant du LPT sont présentés, démontrant sa capacité pour de futures mesures de masse. Dans l'ensemble, les résultats confirment que le dispositif est prêt pour son fonctionnement et qu'une fois optimisé, il permettra d'évaluer l'efficacité globale de la technique de *barium tagging*.

Acknowledgements

First and foremost, I would like to thank Prof. Thomas Brunner for the opportunity to work under him and for his continued guidance, without which this thesis would not have been possible. I could always count on his support. I want to thank Dr. Kevin Murray for his support in the initial years of my PhD. I could always look to him for help, confirmation and received much valuable feedback. Eamon Egan greatly supported the development and troubleshooting of electronics, his expertise in the area was invaluable. Over the years I have also received a lot of support from my colleagues on topics, including but not limited to, physics research, particularly Dr. Sarah Nowicki, Dr. Chris Chambers, Dr. Frédéric Girard and (soon to be Dr.) David Gallacher. I would also like to thank Tomy Arial and Jean Soucy at the Université de Montréal machine shop for their assistance in machining custom parts for the setup. I would also like to thank the **Fonds de recherche du Québec** for supporting my doctoral studies through its funding. I cannot thank my parents enough for their unwavering support in helping me reach where I am today. I am also grateful to my brother for always finding the most unexpected ways to make me smile and brighten difficult days. Finally, thank you, Kesha, for your constant understanding and support throughout my work.

Contribution to original knowledge

The work described in this thesis represents the culmination of several years of research toward the development of a barium tagging technique for the nEXO experiment. My primary contribution was to consolidate these efforts and commission the setup to demonstrate the extraction of ions from gaseous xenon. This involved integrating and validating the performance of the RF funnel and LPT subsystems, which together enable efficient extraction, transport, and preparation of ions for downstream mass spectrometry using the MRTOF-MS.

This thesis focuses on the development and commissioning of the instrumentation aimed at achieving near-perfect extraction and identification of a single ion from a tonne-scale detector. Demonstrating this capability establishes a pathway for current and future liquid xenon based neutrinoless double beta decay experiments to maximize their scientific reach by incorporating barium tagging for background-free operation. This thesis includes the very first results from ions bunched in the LPT and delivered to the MRTOF-MS for mass measurements. Other notable developments include the demonstration of ion extraction from gaseous argon, setting a benchmark for future operation with gaseous xenon, and

the development of a low-cost composite target for a laser ablation ion source that can produce ions over large mass range on demand. Beyond its immediate application to Ba-tagging R&D for nEXO, the instrumentation developed in this work demonstrates broader potential in the precise manipulation and analysis of ions. The integration of a laser ablation ion source, an LPT, and a high-resolution MRTOF-MS constitutes a flexible experimental platform suitable for a wide range of studies, including isotope ratio measurements, trace element analysis, environmental monitoring, and materials characterization. This setup can be employed directly or serve as a foundation for the development of new systems optimized for these applications.

Contribution of Authors

The entire thesis is written by the author. Furthermore, all data analyses and results presented here were done by the author unless otherwise specified with references.

The ion extraction simulations using a capillary were performed by Dr. Robert Collister at Carleton University. The RF funnel was originally designed by Prof. Thomas Brunner in collaboration with Prof. Victor Varentsov¹ and commissioned at Stanford University. RF funnel ion transport simulations were performed by Prof. Victor Varentsov. The RF funnel has since been recommissioned by the author alongside the LPT and the MRTOF. Part of the vacuum system was assembled by Dr. Christopher Chambers, who also designed the RF electronics with Eamon Egan for the RF funnel. This work was later continued by the author who completed the assembly of the vacuum system, electronics for the sextupole ion guide (SPIG), pressure gauge readout, setting up cryopump and compressor control and the control program used to operate the RF funnel.

The LPT was originally designed by Dr. Yang Lan and later modified and machined with the assistance of Xiao Zhang. Voltage switches and RF circuitry for the LPT setup were

¹Facility for Antiproton and Ion Research, Germany

designed at McGill University by Eamon Egan, while the high-voltage switches were designed and supplied by Dr. Peter Schury². The LPT setup was assembled by the author together with Xiao Zhang. The computer aided design (CAD) models for the LPT were prepared by Dr. Yang Lan. The LabVIEW programs used to operate the LPT and the RF funnel, which includes control of a waveform generator, readout of pressure gauges and scanning programs for beam tuning were written by the author. Dr. Kevin Murray and Eamon Egan developed the program for operating the FPGA used to control the timing of voltage switches.

The ion source assembly used with the LPT is based on previous ion source designs at the Brunner Neutrino Lab (BvL) except for a quadrupole bender, which the author designed and optimized in SIMION simulations. The einzel lens assembly installed alongside the quadrupole bender was designed by Dr. Yang Lan and later machined at the Université de Montréal machineshop. The laser ablation source and target were a result of work done by several undergraduate students and was further developed by the author to demonstrate ion production from a variety of materials.

Finally, the MRTOF was designed and commissioned by Dr. Kevin Murray and later used by the author to perform time of flight measurements presented in this work.

²Bespoke Scientific Electronics

Words from the author



This thesis is a consolidation of my work building on a novel idea, barium tagging, which actually can be traced back to the days before we even had conclusive proof of neutrino oscillation (or I was born). It is fascinating that physicists were already developing such ideas even before neutrino oscillations, a key prerequisite for neutrinoless double beta decay, were experimentally observed. I hope that you learn something new from this dissertation and I invite you to contact me (✉ hussain.rasiwala@mail.mcgill.ca) should you have questions or would like to request some of the material presented here.

Note: This thesis uses several hyperlinks to avoid repetition of graphics or information. To have ease in navigating this dissertation, make sure to use the shortcut (for Adobe reader: Alt + ‘←’ / ‘→’, for Preview: Command + ‘[’ / ‘]’) to navigate to the previous or the next redirect.

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List of Acronyms

$0\nu\beta\beta$	neutrinoless double beta decay
$2\nu\beta\beta$	double beta decay
CAD	computer-aided design
CCD	charge-coupled device
CEM	channel electron multiplier
CF	ConFlat
C.L.	confidence level
CMB	cosmic microwave background
CVD	chemical vapor deposition
DC	direct current
DNN	deep neural network
FPGA	field programmable gate array
FWHM	full width at half-maximum
GAr	gaseous argon

GKr	gaseous krypton
GXe	gaseous xenon
HPGe	high-purity germanium
ICB	ion cooler and buncher
IH	inverted hierarchy
LAS	laser ablation ion source
LPT	linear Paul trap
LTQ	linear quadrupole ion trap
LXe	liquid xenon
MRP	mass resolving power
MRTOF-MS	multiple-reflection time-of-flight mass spectrometer
MS	multi-site
MSW	Mikheyev–Smirnov–Wolfenstein
NH	normal hierarchy
NME	nuclear matrix element
OFHC	oxygen-free high thermal conductivity
PEEK	polyether ether ketone
PGV	proportional gate valve
PID	proportional-integral-derivative
PIPS	passivated, implanted, planar silicon

PMNS	Pontecorvo-Maki-Nakagawa-Sakata
PMT	photomultiplier tubes
QMF	quadrupole mass filter
RF	radio frequency
RF funnel	radio frequency funnel
SiPM	silicon photomultipliers
SM	Standard Model of particle physics
SMFI	single-molecule fluorescence imaging
SPIG	sextupole ion guide
SS	single-site
SXe	solid xenon
TFS	time-focus shift
TMP	turbomolecular pump
TOF	time-of-flight
TPC	time projection chamber
TTL	transistor-transistor logic
UHV	ultra-high vacuum
VNA	vector network analyzer
VUV	vacuum-ultraviolet

Introduction

The Universe as we know it is composed of approximately 5% of baryonic matter while dark matter and dark energy make up the remaining 95%, with no significant presence of antimatter [1]. This suggests the existence of a mechanism where matter is preferentially produced over antimatter. Theories, such as leptogenesis, which seek to solve the matter-antimatter asymmetry problem require the violation of lepton number in weak interactions, which is a conserved quantity in the Standard Model of particle physics (SM) [2].

The nEXO experiment seeks to observe the violation of lepton number in the double beta decay ($2\nu\beta\beta$) isotope ^{136}Xe through a hypothetical nuclear decay called neutrinoless double beta decay ($0\nu\beta\beta$) [3]. $0\nu\beta\beta$ involves the simultaneous decay of two neutrons to two protons, producing two electrons but no antineutrinos [4]. This would be the first ever observation of lepton number violation and would imply that neutrinos are their own antiparticles. Due to its significance, the search for $0\nu\beta\beta$ is a top priority for the international subatomic particle physics community. Next-generation experiments, such as nEXO, aim to push the level of sensitivity to $0\nu\beta\beta$ half-lives beyond 10^{28} years at 90% confidence level (C.L.) [5].

To further boost the sensitivity of nEXO, a technique called barium tagging is being

developed as a potential future upgrade. It involves the extraction and identification of the ^{136}Xe double beta decay daughter ^{136}Ba , allowing for the exclusion of all non-double beta decay backgrounds, providing a significant boost in detector sensitivity [6]. The estimated improvement is a factor of 2–3 based on the current estimates of nEXO’s sensitivity [5, 7].

The nEXO detector is a time projection chamber (TPC) that allows for 3D position reconstruction of events. This can be used to locate and extract the Ba ion from a potential $0\nu\beta\beta$ event location. A capillary can then be used to extract the ion along with some liquid xenon (LXe), which, after conversion to gaseous xenon (GXe) gets injected (along with the Ba ion) into a radio frequency funnel (RF funnel). This RF funnel functions as a differential-pumping stage that simultaneously maintains effective ion transmission to an identification system.

The goal for this dissertation is to develop the setup comprising the RF funnel along with a linear Paul trap (LPT) and a multiple-reflection time-of-flight mass spectrometer (MRTOF-MS) to extract ions from GXe and identify them through mass measurements.

The layout of the thesis is as follows: Chapter 1 presents a brief introduction to neutrinos, the history associated with their discovery and various milestones leading to the current state of research into $0\nu\beta\beta$. Chapter 2 provides an overview of TPC technology and the EXO-200 and nEXO experiments. Chapter 3 then introduces the Ba-tagging technique, with an emphasis on the capillary-radio frequency (RF) scheme. Chapter 4 summarizes the theory behind RF ion guides, ion trapping and time-of-flight (TOF) mass spectrometry.

Chapter 5 introduces the Ba-tagging setup for ion extraction and identification from GXe along with the ion detectors and various ion sources used. Chapter 6 and 7 describe the layout of vacuum systems, electronics, and general operation of the RF funnel and LPT subsystems, respectively, and presents the data acquired during their commissioning. Finally, Chapter 8 summarizes the status of the Ba-tagging technique, discusses key results from the commissioning runs, and provides recommendations for future work with the setup.

Chapter 1

Neutrinos: History, Properties, and Physics Motivation

Neutrinos are electrically-neutral leptons that, as far as is known, occur in three distinct types, or “flavors”: the electron-neutrino (ν_e), muon-neutrino (ν_μ), and tau-neutrino (ν_τ), named after their associated charged leptons [8]. As shown in Figure 1.1, neutrinos are the lightest known massive¹ elementary particles, at least a million times lighter than the next heavier particle, the electron [9]. Unlike charged fermions, neutrinos are believed to not acquire mass through the Higgs mechanism, because the SM includes only left-handed neutrinos, and not the right-handed counterparts required to form a Dirac mass term. Their extremely low masses compared to other SM particles suggest that an alternative mechanism may be responsible for neutrino masses, such as the see-saw mechanism [10].

Neutrinos interact with matter almost exclusively via the weak interaction, with a cross

¹Here ‘massive’ is indicative of neutrinos having a non-zero mass, as opposed to particles like the photon or the gluon.

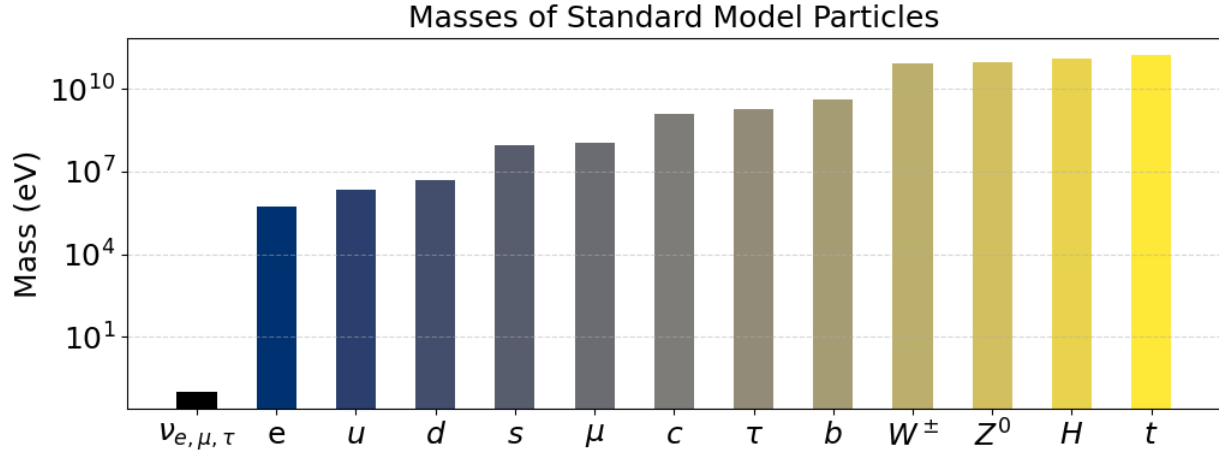


Figure 1.1: Masses of subatomic particles (information extracted from pg.25-33) [11]. The neutrino mass is shown at the current 0.45 eV upper-limit from direct neutrino mass measurements [9].

section of 10^{-38} cm^2 at 1 GeV [11]. The interaction cross section scales with the neutrino energy, making interaction rates at lower energies extremely small and, as a result, experimental studies inherently difficult and often statistically limited [12, 13]. Adding to this complexity, neutrinos exhibit a quantum phenomenon known as flavor oscillations, or more commonly called neutrino oscillations [14]. Through this phenomenon, neutrinos transition between the three flavors as they propagate through space. For example, a ν_e produced in a β^+ decay alongside a positron may later be detected as a ν_μ . The Nobel Prize in Physics 2015 was awarded to Takaaki Kajita and Arthur B. McDonald for their contributions to the discovery of neutrino oscillations [15].

The neutrino was first proposed by Wolfgang Pauli in 1930 as a “desperate remedy” to preserve the conservation of energy and momentum in beta decay [16]. The existence of the

particle was confirmed in 1956, when Clyde Cowan and Frederick Reines successfully detected neutrinos at the Savannah River site near Aiken, South Carolina [17]. Their pioneering experiment used large water tanks containing cadmium chloride (CdCl_2) to capture neutrinos from a nearby nuclear reactor, with a neutrino flux of 10^{13} neutrinos/(s cm²). The detection of the neutrino was confirmed using a three gamma signal coincidence for which Frederick Reines received the Nobel Prize in 1995 [18]. Two prompt gammas are produced as a result of the annihilation of the positron from the capture of an antineutrino:

$$\bar{\nu}_e + p \longrightarrow n + e^+, \quad (1.1)$$

$$e^+ + e^- \longrightarrow 2\gamma, \quad (1.2)$$

and one delayed gamma ($\sim 5 \mu\text{s}$) produced from the capture of the neutron:

$$n + {}^{108}\text{Cd} \longrightarrow {}^{109}\text{Cd}^* \longrightarrow {}^{109}\text{Cd} + \gamma. \quad (1.3)$$

The next neutrino flavor to be detected was ν_μ at Brookhaven National Laboratory in 1962 [19]. A 15 GeV proton beam was used on a Be target to produce a pion beam. This beam was directed towards a 10-tonne spark chamber filled with neon gas. Pions decayed in-flight into muons and neutrinos, with all particles except neutrinos being absorbed by the iron shielding before reaching the detector. Interactions within the chamber produced muons, which were clearly differentiable from electrons because of their long tracks. During

data collection, 34 muon and zero electron candidates were observed [20]. This led to the conclusion that neutrinos produced together with muons in pion decays were different from neutrinos produced with electrons (in β decay for instance). Leon Lederman, Melvin Schwartz, and Jack Steinberger were awarded the Nobel Prize in 1988² for this discovery and for demonstrating the doublet structure of leptons in nature [21]. The τ lepton was discovered in 1975 at Stanford Linear Accelerator Center (SLAC), which motivated the existence of a third neutrino flavor [22]. The ν_τ was discovered in 2000 at Fermi National Laboratory by the DONuT experiment [23].

The properties that make studying neutrinos difficult also open new pathways for studying new physics, particularly from extraterrestrial sources. Since neutrinos rarely interact with matter, they can travel large distances without scattering or absorption. For example, neutrinos are ideal candidates to study the fusion process of the Sun. The Homestake experiment was one of the pioneering experiments in this field [24]. The goal of the experiment was to compare solar neutrino production rates with theoretical predictions to confirm our understanding of the fusion mechanism in the Sun. The Homestake experiment became the first to detect neutrinos from the Sun, recognized by a Nobel Prize in 2002 [25]. However, an observation from this experiment was that the measured rates were approximately one-third of the predicted values. This difference was later confirmed by several other experiments and was coined as the ‘solar neutrino problem’ [26]. This

²Surprisingly, this discovery was awarded Nobel Prize before the discovery of the first neutrino.

reproducible difference between prediction and observation motivated further research into the neutrinos.

1.1 Neutrino oscillations

With continued improvements in detector sensitivities and careful re-evaluation of expected neutrino rates, it became clear that no amount of modifications to the solar models could explain the missing neutrinos. A major breakthrough took place in 1997 with the observation of neutrino oscillations by two independent experiments, SNO and Super-Kamiokande which helped solve the mystery of the missing solar neutrinos [27, 28]. The key factor was the sensitivity to other neutrino flavors and not just to ν_e . Results showed two key findings: first, the sum of detected neutrinos, independent of neutrino flavors, matched predicted rates; second, the rate of electron neutrinos was a third of the total neutrino flux. The experiments found that the missing fraction of solar neutrinos (originally ν_e) reappeared as a different flavor neutrino (ν_μ) and confirmed a total flux consistent with the neutrino production rate expected from processes in the Sun.

The discovery of neutrino oscillation provided the first direct evidence of the existence of physics beyond the SM. A major implication of this discovery was that at least two of the three neutrino mass eigenstates had to be non-zero, thereby opening new avenues of research to better understand the nature of neutrinos.

Neutrino oscillations are a quantum mechanical process in which a neutrino propagates

as a superposition of mass eigenstates with each state advancing at a rate related to their corresponding mass. The three neutrino flavor states (ν_e , ν_μ and ν_τ) can be described as a superposition of neutrino-mass eigenstates with definite and non-degenerate masses (ν_1 , ν_2 and ν_3) via the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [29] as:

$$|\nu_a(t)\rangle = \sum_{k=1}^3 U_{ak} |\nu_k(t)\rangle, \quad (1.4)$$

where, $a = e, \mu, \tau$ (flavor index), $k = 1, 2, 3$ (mass index), and U_{ak} is the PMNS matrix element. The PMNS matrix is a product of three rotation matrices corresponding to the mixing angles (θ_{12} , θ_{13} , θ_{23}), and the CP phase (δ_{CP}) such that:

$$\begin{aligned} U_{\text{PMNS}} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P \\ &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} P. \end{aligned}$$

Here, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and matrix P depends on the nature of the neutrino. Specifically, P is the identity matrix for Dirac neutrinos, whereas for Majorana neutrinos it

takes the form $P = \text{diag}[1, e^{i\alpha}, e^{i\beta}]$, where α and β are the Majorana phases.

The estimates for the three mixing angles are obtained by studying the three main sources of neutrinos: θ_{12} - solar neutrinos; θ_{23} - atmospheric neutrinos, produced by cosmic rays in the Earth's atmosphere; and θ_{13} - reactor neutrinos, which are electron antineutrinos from nuclear fission in nuclear reactors [30–32]. Complementary measurements are also performed across a wide range of baselines, from a few meters to long-baseline ($L \geq 100$ km), by neutrino oscillation experiments that utilize accelerator-produced neutrino beams [33, 34]. Using detectors at different distances, the neutrino fluxes and flavor compositions can be compared to determine the oscillation parameters.

Using Equation 1.4 with the ultra-relativistic limit, the probability of oscillation from flavor a to b can be expressed as:

$$P_{\nu_a \rightarrow \nu_b}(t) = \sum_{k,j=1}^3 U_{ak} U_{bk}^* U_{aj}^* U_{bj} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right), \quad (1.5)$$

where L is the distance traveled, E is the neutrino energy, and $\Delta m_{kj}^2 = m_k^2 - m_j^2$ is the squared mass difference of mass eigenstates ($|\nu_k\rangle, |\nu_j\rangle$). Using known values of neutrino energy and distance traveled, the measured difference in detection rates can be used to calculate the values for $|\Delta m_{21}^2|$ and $|\Delta m_{31}^2|$. The absolute value for Δm_{21}^2 is known from measurement of the Mikheyev–Smirnov–Wolfenstein (MSW) effect with solar neutrinos but the sign for Δm_{31}^2 remains undetermined [35]. The possibility of $m_2 > m_3 > m_1$ is ruled

out since $\Delta m_{31}^2 \gg \Delta m_{21}^2$. This gives rise to two possible orderings or hierarchies of the neutrino masses: normal hierarchy (NH) for $m_3 > m_2 > m_1$ and inverted hierarchy (IH) for $m_2 > m_1 > m_3$. The most current bounds for the oscillation parameters for the two mass hierarchies are summarized in Table 1.1. Experiments studying neutrino oscillations continue to improve the precision of the measured parameters. Next-generation experiments such as DUNE, Hyper-Kamiokande, and JUNO are being designed to probe charge-parity violation in the neutrino sector and determine the neutrino mass hierarchy [36–38].

Since neutrino oscillation implies non-zero neutrino masses, neutrino helicity and chirality are no longer identical, i.e. a left-handed neutrino in one reference frame can appear right-handed in another frame moving sufficiently fast. Because only right-handed antineutrinos and left-handed neutrinos participate in weak interactions, the non-conservation of helicity suggests that there may be no fundamental distinction between a neutrino and its antineutrino. The neutrino and antineutrino could, in fact, be the same particle, implying that neutrinos are Majorana particles. One of the most sensitive experimental approaches to probe this hypothesis is through the search for neutrinoless double beta decay ($0\nu\beta\beta$) [39].

1.2 Neutrinoless Double Beta Decay

Marie Goeppert-Mayer is well known for her work on the nuclear shell model in the 1950s, which ultimately led to her being awarded the Nobel Prize in Physics in 1963 [40]. In addition

Parameter	Normal Hierarchy (NH)	Inverted Hierarchy (IH)
$\sin^2 \theta_{12}$	0.307 ± 0.013	
$\Delta m_{21}^2 [\text{eV}^2]$	$(7.53 \pm 0.18) \times 10^{-5}$	
$\sin^2 \theta_{23}$	$0.558^{+0.015}_{-0.021}$	$0.553^{+0.016}_{-0.024}$
$\Delta m_{31}^2 [\text{eV}^2]$	$(2.455 \pm 0.028) \times 10^{-3}$	$-(2.529 \pm 0.029) \times 10^{-3}$
$\sin^2 \theta_{13}$	$(2.19 \pm 0.07) \times 10^{-2}$	
$\delta_{\text{CP}} [\text{rad}]$	$1.19 \pm 0.22 \pi$	

Table 1.1: Neutrino oscillation parameters for normal and inverted mass hierarchies [11].

to these later contributions, her earlier work laid important foundations in nuclear physics, including the proposal of double beta decay in 1935 [41]. The process was expected to occur in nuclei where β -decay is energetically forbidden, resulting in the nuclei decaying by two simultaneous beta decays. The double beta decay of a nucleus X can be expressed as:

$${}^Z_A X \rightarrow {}^{Z+2}_A Y + 2e^- + 2\bar{\nu}_e + Q_{\beta\beta}, \quad (1.6)$$

where Y is the daughter nucleus and $Q_{\beta\beta}$ is the energy released from the decay that is typically carried by the two e^- and two $\bar{\nu}_e$ produced. Figure 1.2 shows an example of one such nucleus that is ${}^{136}\text{Xe}$. The double beta decay of ${}^{136}\text{Xe}$ bypasses single beta decay to ${}^{136}\text{Cs}$, which is energetically forbidden, and decays to ${}^{136}\text{Ba}$ as indicated by the nuclear masses. Double beta decay is a second-order weak interaction process and is therefore

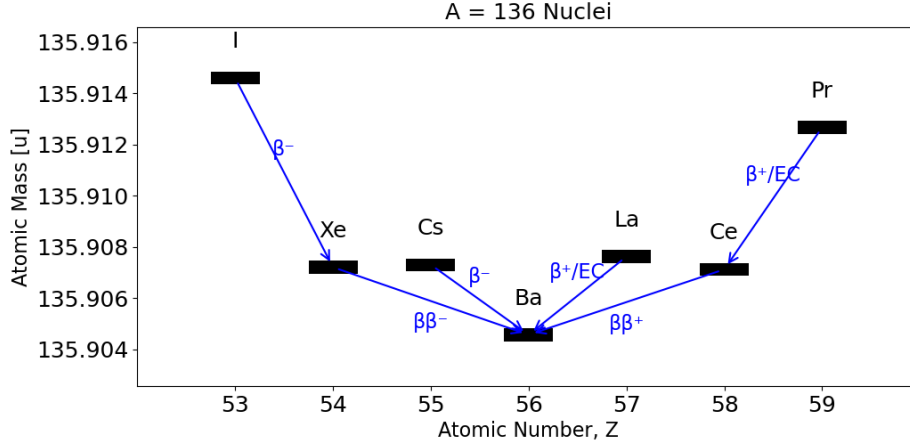


Figure 1.2: $A = 136$ isobars and their decay pathways toward ^{136}Ba . Since the β -decay from ^{136}Xe to ^{136}Cs is energetically forbidden, the nucleus instead undergoes energetically allowed double beta decay directly to ^{136}Ba . Data from [43].

relatively slow. From the 40+ nuclei that are theoretically capable of undergoing double beta decay, the process has been observed in over twelve even-even nuclei [42]. Table 1.2 lists the measured half-lives of double beta decay of the isotopes most commonly studied.

Building on the idea of double beta decay, in 1939 W. H. Furry proposed that if neutrinos were Majorana fermions, one could observe lepton number violation in the double beta decaying nuclei [57, 58]. This concept laid the theoretical foundation for modern day searches of neutrinoless double beta decay. Figure 1.3 compares the Feynman diagrams of the observed double beta decay ($2\nu\beta\beta$) with the hypothetical neutrinoless double beta decay ($0\nu\beta\beta$) where no electron antineutrinos are produced,

$${}^Z_A X \rightarrow {}^{Z+2}_A Y + 2e^- + Q_{\beta\beta}, \quad (1.7)$$

Isotope	$T_{1/2}^{2\nu}$ (years)	$T_{1/2}^{0\nu}$ limit (years)	Experiment
^{48}Ca	$(6.4 \pm 1.2) \times 10^{19}$	$> 5.8 \times 10^{22}$	NEMO-3, UMEHARA [44, 45]
^{76}Ge	$(2.022 \pm 0.018 \pm 0.038) \times 10^{21}$	$> 1.9 \times 10^{26}$	GERDA, LEGEND-200 [46, 47]
^{82}Se	$(8.69^{+0.09}_{-0.06} \pm 0.05) \times 10^{19}$	$> 4.6 \times 10^{24}$	CUPID-0 [48, 49]
^{100}Mo	$(7.07 \pm 0.02 \pm 0.11) \times 10^{18}$	$> 1.8 \times 10^{24}$	CUPID-Mo [50, 51]
^{130}Te	$(6.9 \pm 1.3) \times 10^{20}$	$> 3.2 \times 10^{25}$	CUORE [52, 53]
^{136}Xe	$(2.165 \pm 0.016 \pm 0.059) \times 10^{21}$	$> 3.8 \times 10^{26}$	EXO-200, KamLAND-Zen [54, 55]
^{150}Nd	$(9.34^{+0.62}_{-0.6} \pm 0.22) \times 10^{18}$	$> 2.0 \times 10^{22}$	NEMO-3 [56]

Table 1.2: Summary of measured double beta decay ($2\nu\beta\beta$) half-lives and experimental lower limits on neutrinoless double beta decay ($0\nu\beta\beta$) half-lives.

violating the lepton number conservation by 2. The actual mechanism behind $0\nu\beta\beta$ is unknown, the black box in the diagram is symbolic to the Schechter-Valle (black box) theorem that implies that the observation of $0\nu\beta\beta$ always indicates new physics beyond the Standard

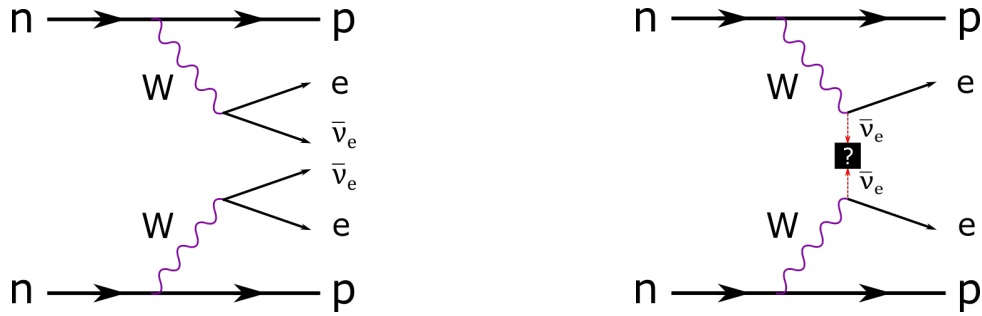


Figure 1.3: Feynman diagrams illustrating (left) two-neutrino double beta decay and (right) neutrinoless double beta decay. The black box here signifies that the underlying mechanism responsible for neutrinoless double beta decay is not yet known.

Model [59]. Research into neutrinos through the study of $0\nu\beta\beta$ has the potential to provide insight into the mechanism of neutrino mass generation and to address fundamental questions about leptogenesis and, consequently, the matter–antimatter asymmetry of the Universe [60].

The most accessible experimental signal available for detection of $0\nu\beta\beta$ events is through the energy carried by electrons. Figure 1.4 compares the summed electron energy spectra from $2\nu\beta\beta$ and $0\nu\beta\beta$. Since no electron antineutrinos are emitted in $0\nu\beta\beta$, and the nuclear recoil is negligible due to the large mass of the daughter nucleus, the full decay energy, $Q_{\beta\beta}$, is carried by the two emitted electrons. As a result, the $0\nu\beta\beta$ signal appears as a peak at the endpoint of the continuous $2\nu\beta\beta$ spectrum. Rather than a sharp peak at $Q_{\beta\beta}$, the $0\nu\beta\beta$ spectrum shown in Figure 1.4 includes smearing which is characteristic of finite detector resolution. As a consequence of lepton number violation, $0\nu\beta\beta$ is highly suppressed, and only lower bounds on its half-life have been measured to date. This is reflected in the relative decay rates of $2\nu\beta\beta$ and $0\nu\beta\beta$, with the latter expected to be many orders of magnitude rarer. In Figure 1.4, the inset highlighting the $0\nu\beta\beta$ peak is shown with an assumed relative scaling of 10^6 . In practice, the scaling can be significantly larger, as the expected $0\nu\beta\beta$ signal is exceedingly rare and must be distinguished from various background contributions that can populate the region around $Q_{\beta\beta}$.

The $0\nu\beta\beta$ half-lives of the most commonly studied nuclei are presented alongside their $2\nu\beta\beta$ half-lives in Table 1.2. In the light-neutrino exchange model, wherein $0\nu\beta\beta$ is mediated

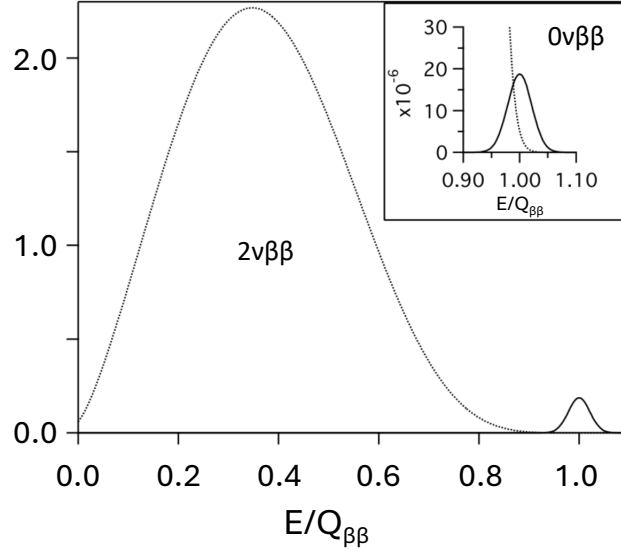


Figure 1.4: Representation of the electron energy spectrum from $2\nu\beta\beta$ and $0\nu\beta\beta$. Figure reproduced from [61].

by the exchange of light Majorana neutrinos (≤ 1 eV), the half-life ($T_{1/2}^{0\nu}$) is given by:

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}. \quad (1.8)$$

Here, $M^{0\nu}$ denotes the nuclear matrix element (NME), $G^{0\nu}$ the phase-space factor, and m_e the electron mass. The search for $0\nu\beta\beta$ with different isotopes is motivated by the fact that each isotope provides complementary sensitivity owing to differences in NMEs and phase-space factors. $m_{\beta\beta}$ is referred to as the effective neutrino mass which is related to the

neutrino mass eigenvalues m_i through:

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^N U_{ei}^2 m_i \right|, \quad (1.9)$$

where U_{ij} are the PMNS matrix elements for $i = (1, \dots, N)$, and $N = 3$ for the standard $[3 \times 3]$ PMNS matrix³. Experimental lower limits on the neutrinoless double beta decay half-life, $T_{1/2}^{0\nu}$, provide a means to infer the effective Majorana mass $m_{\beta\beta}$. Consequently, constraints on $m_{\beta\beta}$ from $0\nu\beta\beta$ searches translate into indirect limits on the absolute neutrino mass scale, assuming neutrinos are Majorana particles.

The only direct approach to studying neutrino masses is through direct neutrino mass (m_β) measurement by precision spectroscopy of the kinematic endpoint of beta decay. This approach of neutrino mass scale estimation offers a model-independent approach. The current upper-limit from kinematic searches comes from the measurement of the β decay endpoint of ${}^3\text{H}$ by the KATRIN experiment [9]:

$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{\frac{1}{2}} < 0.45 \text{ eV}. \quad (1.10)$$

This limit is much higher than the 0.072 eV limit from cosmology through studies of the cosmic microwave background (CMB) on the sum of neutrino masses ($\sum m_i$) [63]. Figure 1.5 shows the effective Majorana mass, $m_{\beta\beta}$, as a function of the lightest neutrino

³Non-standard models include frameworks like 3+1 that include sterile neutrinos [62].

mass. Depending on the assumed neutrino mass hierarchy, the relevant lightest mass eigenvalue is m_1 in the case of NH and m_3 for IH. The uncertainty associated with the unknown Majorana phases, the neutrino oscillation parameters, and the different mass orderings gives rise to two distinct allowed regions corresponding to the two hierarchies. Also shown in Figure 1.5 are exclusion regions derived from constraints on the absolute neutrino mass scale obtained via kinematic measurements and cosmological observations, as well as limits on the effective Majorana mass from $0\nu\beta\beta$ searches. Despite their differing sensitivities and underlying assumptions, these approaches are complementary, as they probe different combinations of neutrino mass eigenstates and provide independent constraints on the neutrino mass scale.

To translate these mass-scale constraints into experimental sensitivity, it is necessary to connect $m_{\beta\beta}$ to the observable decay rate of the process. This is achieved through the relationship between $m_{\beta\beta}$ and the neutrinoless double beta decay half-life, $T_{1/2}^{0\nu}$, which provides the direct experimental figure of merit in $0\nu\beta\beta$ searches. Assuming a background free experiment, $T_{1/2}^{0\nu}$ is given by:

$$T_{1/2}^{0\nu} = \frac{\ln 2}{W} \frac{N_A}{N} (a\epsilon Mt), \quad (1.11)$$

where M is the total mass of the detector material, W is the molar mass of the material, N_A is the Avogadro number, ϵ is the detection efficiency, a is the natural isotopic abundance

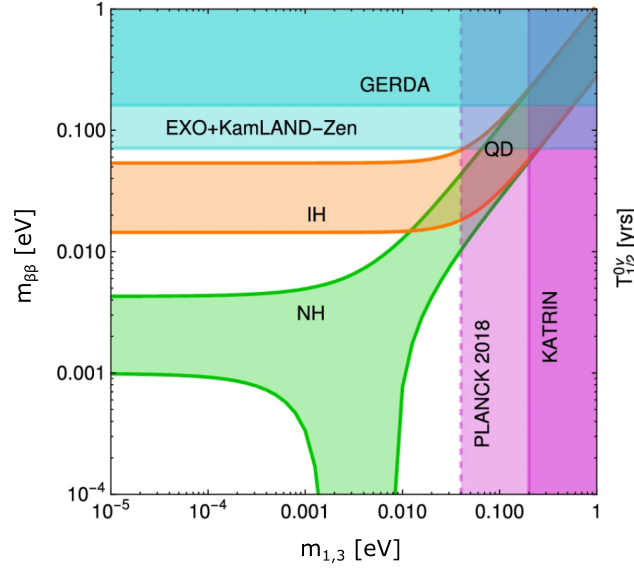


Figure 1.5: Effective Majorana mass ($m_{\beta\beta}$) as a function of the lightest neutrino mass (m_1 or m_3 , depending on the mass ordering). The allowed bands for $m_{\beta\beta}$ (orange: IH, green: NH) reflect uncertainties in the Majorana phases and neutrino mass ordering. Horizontal bands indicate constraints on $m_{\beta\beta}$ from $0\nu\beta\beta$ experiments such as EXO-200, KamLAND-Zen, and GERDA experiments. Vertical bands correspond to limits from direct neutrino mass measurements by the KATRIN experiment and cosmological constraints from PLANCK 2018 CMB data. Figure reproduced from [64].

of the $0\nu\beta\beta$ nuclei, t is the livetime of the detector and N is the number of $0\nu\beta\beta$ events observed. Several measures are taken in designing experiments to reduce backgrounds in the energy region of interest at $Q_{\beta\beta}$. In practice, achieving a truly background-free experiment is unrealistic and background contributions must be carefully incorporated into the estimation of $T_{1/2}^{0\nu}$. Assuming a background rate B_c and energy resolution of the detector ΔE , the total

number of background events can be calculated as:

$$B_c = B M t \Delta E. \quad (1.12)$$

For a statistically significant result, the number of events N observed should be greater than the uncertainty in B_c . Based on the expectation that background events follow a Poisson distribution:

$$N \geq n_\sigma \sqrt{B_c}, \quad (1.13)$$

where n_σ is the number of standard deviations based on a given C.L. ($n_\sigma = 1.645$ for 90% C.L.) [65]. Substituting Equations 1.12 and 1.13 in Equation 1.11 gives,

$$T_{1/2}^{0\nu} = \frac{\ln 2}{n_\sigma W} (a\epsilon N_A) \sqrt{\frac{M t}{B \Delta E}}. \quad (1.14)$$

From Equations 1.14 and 1.8, the estimated half-life $T_{1/2}^{0\nu}$ can be combined with NMEs to place an upper limit on the effective neutrino mass [66]. These relations make it clear that probing smaller neutrino masses requires detectors with larger target masses, high energy resolution, and lower background rates. Thus, $0\nu\beta\beta$ experiments deploy large detectors constructed from carefully screened radio-pure materials and sited in underground laboratories with large rock overburden to suppress backgrounds from cosmic radiation sources [67, 68].

Table 1.2 provides lower limits of $0\nu\beta\beta$ half-lives for various nuclei. Among the listed nuclei, the highest half-life limits were measured in the isotopes ^{76}Ge and ^{136}Xe which approximately corresponds to $m_{\beta\beta} \geq 0.1 \text{ eV}$. The goal of next generation experiments, such as nEXO, is to push this limit further to reach $m_{\beta\beta} \sim 0.01 \text{ eV}$ to effectively exclude the inverted mass hierarchy for Majorana neutrinos [5]. From Equation 1.8, using representative values of $|M^{0\nu}|^2 \sim 10$ and $G \sim 10^{-14} \text{ years}^{-1}$ [69]:

$$T_{1/2}^{0\nu} = (G|M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 m_e^{-2})^{-1} \approx 10^{28} \left(\frac{0.01 \text{ eV}}{\langle m_{\beta\beta} \rangle} \right)^2. \quad (1.15)$$

To probe half-lives of order 10^{28} years with event rates (R) of at least ~ 1 decay per year:

$$R = \frac{\ln(2)}{T_{1/2}^{0\nu}} N, \quad (1.16)$$

$$N = \frac{T_{1/2}^{0\nu} R}{\ln(2)} \sim 10^{28} \text{ atoms}. \quad (1.17)$$

Converting this to a detector mass for ^{136}Xe ,

$$M = \frac{N A}{N_A} \sim \mathcal{O}(10^6) \text{ g} \sim 1 \text{ tonne}, \quad (1.18)$$

where $A = 136 \text{ g/mol}$ is the molar mass and N_A is Avogadro's number. Achieving such sensitivities therefore necessitates detectors with tonne-scale active masses. Consequently, next-generation $0\nu\beta\beta$ experiments such as LEGEND, nEXO, and XLZD are all designed at

the tonne scale to reach half-life sensitivities approaching 10^{28} years.

1.3 Theoretical and Experimental Status of Neutrinoless Double Beta Decay

The search for $0\nu\beta\beta$ is driven by both novel theoretical developments and large-scale experimental efforts aimed at establishing the Majorana nature of neutrinos and probing the absolute neutrino mass scale. This section provides a brief overview of the current theoretical framework, with emphasis on NME calculations, followed by an introduction of the leading experimental programs.

1.3.1 Nuclear Matrix Elements and *Ab Initio* Approaches

The interpretation of $0\nu\beta\beta$ searches in terms of the effective Majorana mass, $m_{\beta\beta}$, relies critically on the evaluation of NMEs. Equation 1.8 showed the dependence of $0\nu\beta\beta$ on $G^{0\nu}$, the phase-space factor and $M^{0\nu}$, the NME. $G^{0\nu}$, which is the more precisely calculated quantity of the two, encodes the kinematic phase space available to the emitted electrons and depends on the decay energy $Q_{\beta\beta}$. To leading order, it scales as $G^{0\nu} \propto Q_{\beta\beta}^5$, reflecting the phase space available for the two-electron final state [70, 71]. On the other hand, theoretical uncertainty in $M^{0\nu}$ remains one of the dominant limitations in extracting precise values of $m_{\beta\beta}$. The complexity in the NME computation is due to the fact that it requires the solving of a many-body problem to accurately determine the nuclear wavefunctions.

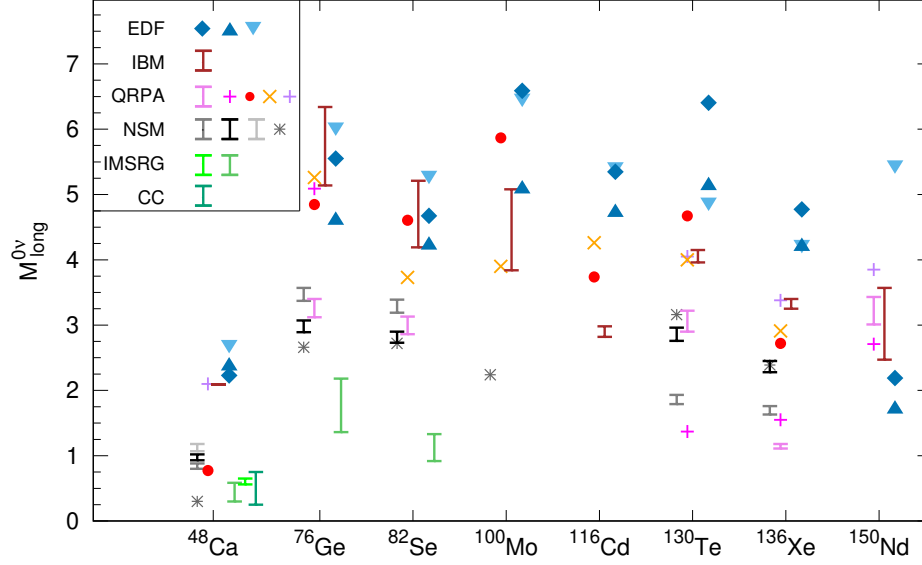


Figure 1.6: Comparison of calculated $0\nu\beta\beta$ NMEs $M^{0\nu}$ for several candidate isotopes using different theoretical approaches. Different symbols within a given method denote results obtained under varying underlying model assumptions. Figure reproduced from [60].

Figure 1.6 shows the values for unitless NME computed for several $0\nu\beta\beta$ candidate isotopes using various many-body methods.

The model dependent nature of these methods such as quasiparticle random phase approximation (QRPA), the interacting boson model (IBM), and energy density functional (EDF) leads to a spread in predicted NMEs of typically a factor of 2–3 [72]. In recent years, *ab initio* methods such as the coupled-cluster (CC) theory, and the in-medium similarity renormalization group (IMSRG) have made significant progress [73, 74]. These approaches aim to derive nuclear properties starting from realistic two and three body

interactions rooted in chiral effective field theory. Although currently limited to lighter nuclei or truncated model spaces, ongoing developments are extending their applicability toward medium-mass systems relevant for $0\nu\beta\beta$, including ^{76}Ge and ^{136}Xe . These efforts are crucial in reducing theoretical uncertainties and improving the reliability of the neutrino mass limits [75].

1.3.2 Experimental Searches for $0\nu\beta\beta$

A vigorous global effort is underway to search for $0\nu\beta\beta$ in multiple candidate isotopes, through diverse detection techniques. These experiments aim to achieve ultra-low background conditions, excellent energy resolution, and large target masses to maximize sensitivity to long half-lives exceeding 10^{28} years. In this section, selected past and upcoming experiments focusing on two leading isotopes, ^{76}Ge and ^{136}Xe , are discussed.

Searches in ^{76}Ge

A combination of relatively high natural abundance (7.8%) and a $Q_{\beta\beta}$ value of 2.039 MeV makes ^{76}Ge a strong candidate for $0\nu\beta\beta$ searches. The high $Q_{\beta\beta}$ places the $0\nu\beta\beta$ signal above most naturally occurring radioactive backgrounds arising from trace contaminants in detector materials. Additionally, the enrichment and purification techniques for germanium are well established [76]. Experiments using ^{76}Ge leverage the well-established detector technology based on high-purity germanium (HPGe) detectors. An example is the GERDA

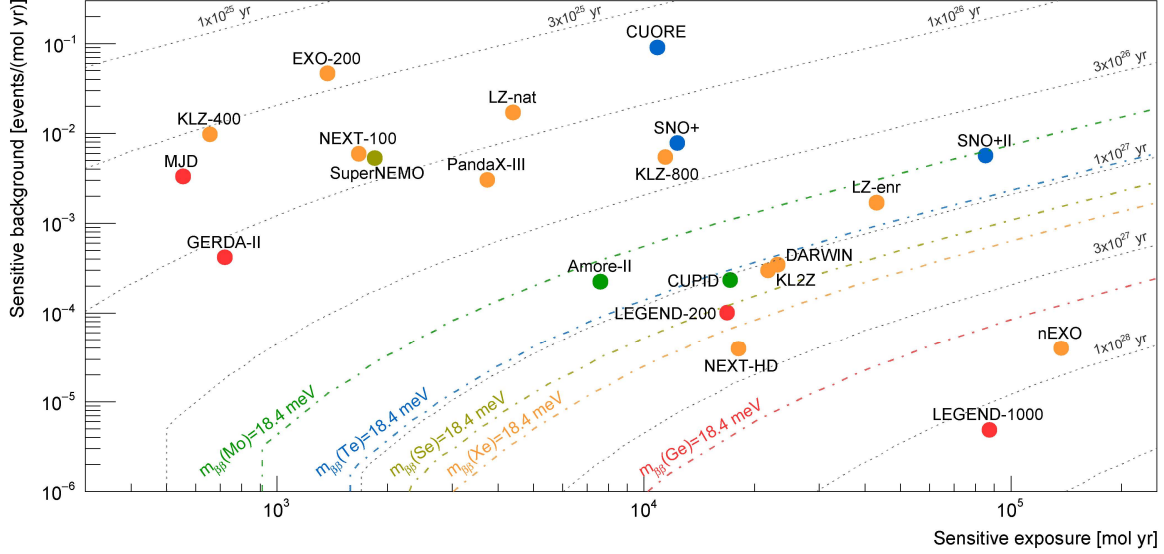


Figure 1.7: Background rates and exposure for $0\nu\beta\beta$ experiments. The colored dashed lines indicate the minimum half-life sensitivity required for each candidate isotope to fully probe the corresponding IH region. Figure reproduced from [60].

(GERmanium Detector Array) experiment, which operated at the Gran Sasso National Laboratory and utilized bare HPGe detectors. The HPGe crystals were enriched to $\sim 87\%$ in ^{76}Ge and immersed in liquid argon, which served both as a coolant and an active background veto. GERDA achieved a background index below 10^{-3} counts/(keV·kg·years) and set a lower limit on the $0\nu\beta\beta$ half-life of $T_{1/2}^{0\nu} > 1.8 \times 10^{26}$ years at 90% C.L. [77].

Building on the successes of GERDA and another ^{76}Ge -based experiment, the Majorana Demonstrator (MJD), the LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay) collaboration aims to scale up the detector mass while further reducing backgrounds. The first phase, LEGEND-200, is currently operating, with

a target sensitivity beyond 10^{27} years. A future phase, LEGEND-1000, aims to reach sensitivities approaching 10^{28} years, probing the entire IH region [47, 78].

Searches in ^{136}Xe

^{136}Xe is another popular choice for $0\nu\beta\beta$ experiments due to its relatively high $Q_{\beta\beta}$ of 2.459 MeV, appreciable natural abundance of 8.9%, and relative ease of enrichment [79]. Xenon-based experiments offer the advantage of scalability to large target masses and flexibility in detector design, using gas, liquid, and dissolved xenon techniques. The EXO-200 experiment was a TPC that operated with approximately 200 kg of LXe enriched to 80.6% in ^{136}Xe . Through its event reconstruction capabilities and using energy and topology discrimination, EXO-200 set a lower limit of $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ years [80]. Another such experiment is the KamLAND-Zen experiment which employs a large volume of liquid scintillator loaded with enriched xenon, achieving very low background levels through shielding and purification techniques. It set the most stringent half-life limit for $0\nu\beta\beta$ in ^{136}Xe to date, with $T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ years [55].

The next-generation experiment, nEXO, is designed as a multi-tonne-scale LXe TPC with a target mass of approximately 5 tonnes of enriched ^{136}Xe to reach sensitivities beyond 10^{28} years [3, 5]. To further enhance background rejection and reach the ultimate discovery sensitivity, where the only remaining experimental background is the $2\nu\beta\beta$, R&D efforts are ongoing towards developing and demonstrating barium tagging, a technique aimed at

identifying the daughter, ^{136}Ba , produced in a $0\nu\beta\beta$ event.

The XLZD experiment is another proposed multi-tonne-scale LXe detector that, while primarily designed for dark matter searches, also offers significant potential for contributing to $0\nu\beta\beta$ studies [81]. By combining the target masses and technologies of experiments such as LZ and XENONnT, XLZD aims to achieve unprecedentedly low background levels and excellent energy resolution in a large, homogeneous detector volume. Although it is not optimized for $\beta\beta$ decay topology reconstruction in the same way as dedicated xenon TPC experiments like nEXO, its enormous exposure to ^{136}Xe and ultra-low background environment could enable competitive sensitivity to a $0\nu\beta\beta$ half life of 1.3×10^{28} years at 90% C.L. [82].

Together, these experimental efforts, combined with advances in nuclear theory, are steadily improving sensitivity to $0\nu\beta\beta$ and narrowing the parameter space for the effective Majorana mass. The following chapter introduces the TPC technology used in $0\nu\beta\beta$ searches with ^{136}Xe and describes the detector design and research program of the nEXO experiment.

Chapter 2

Search for $0\nu\beta\beta$ with the nEXO Experiment

The search for $0\nu\beta\beta$ is challenging due to the extremely low decay rates corresponding to half-lives over 10^{26} years. To have a realistic chance of observing even a few events per year, experiments must employ large quantities of the double beta decaying isotope. In this respect, LXe is an attractive detection medium, as it combines several key advantages: self-shielding due to its high stopping power ($Z = 54$), chemical inertness, relative ease of purification, and ability to produce scintillation light.

This chapter outlines the experimental approach to searching for $0\nu\beta\beta$ in ^{136}Xe . It begins with an introduction to TPC technology, which underpins xenon-based experiments, followed by a review of the EXO-200 experiment, and concludes with an overview of the nEXO detector and its design.

2.1 Time Projection Chambers

The occurrence of $0\nu\beta\beta$ is primarily detected through the energy $Q_{\beta\beta}$ released. Figure 1.4 showed an example of the energy spectrum expected from $2\nu\beta\beta$ and $0\nu\beta\beta$ events. Experiments searching for $0\nu\beta\beta$ focus on minimizing backgrounds and maximizing energy resolution in the regions around $Q_{\beta\beta}$. Among the various detector technologies available for rare-event searches such as the search for $0\nu\beta\beta$, TPCs are one of the leading choices [83, 84].

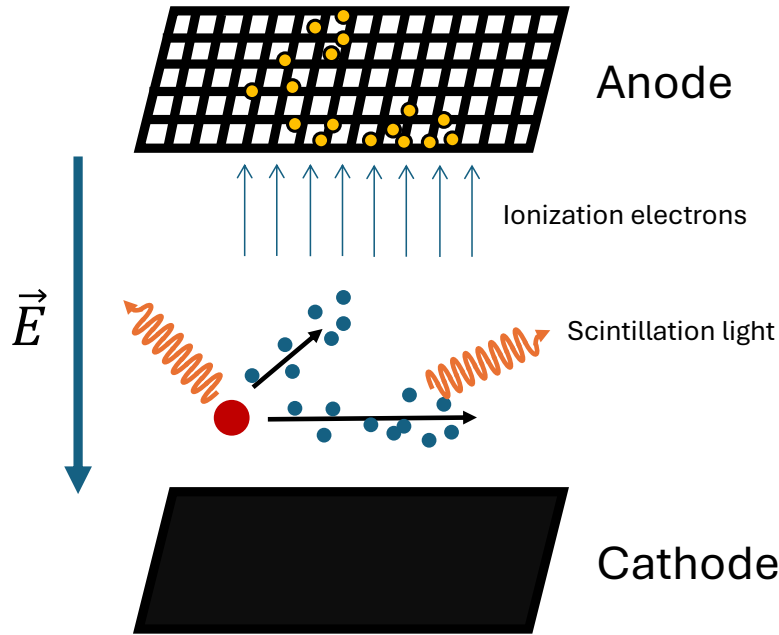


Figure 2.1: A basic TPC design consists of a vessel with a homogeneous electric field applied between the cathode and anode. Information about particle interactions is obtained from ionization electrons and scintillation light produced in the process.

The basic design of a TPC includes a fluid filled vessel, which in the context of $0\nu\beta\beta$ will either be the element in gaseous or liquid form, enriched in the candidate isotope or a scintillating material with the candidate isotope dissolved in it. A homogeneous electric field is applied across the volume of the vessel, with a cathode and an anode on opposite ends for a single-sided TPC or with the cathode in the center and two anodes on opposite sides for a double-sided TPC. Particle interactions and other events inside the vessel cause the detector material to ionize and produce electrons. The electric field causes the electrons to drift towards the anode where they are detected. The particle interactions also produce scintillation light resulting from the excitation of the scintillating material. The scintillation light produced is proportional to the net energy deposited by the events and hence can be used to obtain an estimate. Unlike electrons that are drifted towards the anode that can take up to 0.1 ms, scintillation light is detected instantaneously and hence also provides the accurate timing information of the events [85]. When combined with the spatial information from the collected electrons and their arrival time at the anode, the event can be fully reconstructed in three dimensions. If the anode readout provides (x, y, t) for the collected electrons, scintillation signal provides t_0 such that:

$$(x, y, z) = (x, y, v_D \times (t - t_0)), \quad (2.1)$$

where v_D is the electron drift velocity. Event reconstruction is one of the defining features of

TPCs, providing detailed information on the interaction location and topology, and playing a crucial role in discriminating against background events with overlapping energy spectra in the region of interest around $Q_{\beta\beta}$. Aside from event topology, the ratio of ionization electrons and scintillation further delivery information of event characteristics.

2.2 The EXO-200 Experiment

The EXO-200 experiment was conceived as a demonstrator for the search for $0\nu\beta\beta$ using the isotope ^{136}Xe [86]. The experiment was located 655 m underground at the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA. The detector consisted of a single-phase cylindrical TPC containing 175 kg of LXe enriched to 80.6% in ^{136}Xe . A common cathode splits the LXe volume in two equal halves, each of radius 18 cm and drift length of ~ 20 cm. Charge and scintillation signals were read out using crossed wire planes and large-area avalanche photodiodes (LAAPDs) installed at both ends of the TPC. The TPC was enclosed within a cryostat to maintain the LXe temperature and surrounded by approximately 25 cm of lead shielding, along with an active cosmic-ray veto system. Figure 2.2 shows schematics of the EXO-200 experiment and the TPC.

Event energies were reconstructed by exploiting the anti-correlation between ionization charge and scintillation light. In addition, events were classified as single-site (SS) or multi-site (MS) based on the multiplicity of energy depositions, with $0\nu\beta\beta$ signals expected to appear predominantly as SS events. The experiment operated in two data-taking phases:

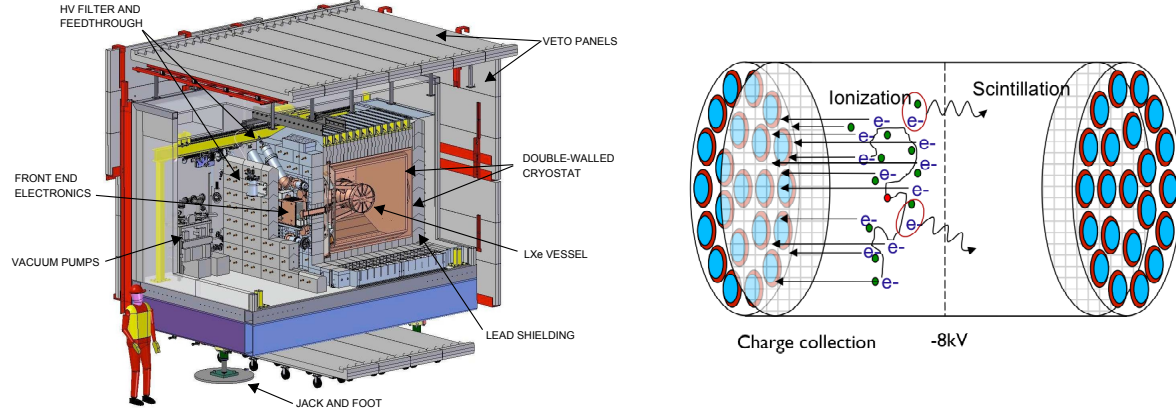


Figure 2.2: Schematics of the EXO-200 experiment. (Left) Rendering of the experiment showing lead shielding, detector, cryostat, electronics and vacuum components. (Right) Schematic of the EXO-200 detector with a central cathode, anodes, and LAAPDs on either end. Reproduced from [86].

Phase-I (2011–2014) and Phase-II (2016–2018), the latter incorporating upgraded electronics to improve energy resolution. The average energy resolution at $Q_{\beta\beta}$, expressed as σ/E , was determined using calibration sources such as ^{228}Th , ^{226}Ra , and ^{60}Co , yielding $1.35 \pm 0.09\%$ for Phase-I and $1.15 \pm 0.02\%$ for Phase-II. EXO-200 was the first experiment to observe $2\nu\beta\beta$ in ^{136}Xe with a measured half life of 2.165×10^{21} years [54, 87]. Using the combined data from both phases, the experiment set a lower limit on the $0\nu\beta\beta$ half-life of $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ years at 90% C.L. [80].

Building on the success of EXO-200, the next-generation nEXO experiment aims to significantly enhance sensitivity to $0\nu\beta\beta$ by scaling the detector mass to the tonne scale to probe $0\nu\beta\beta$ half-lives beyond 10^{28} years.

2.3 Overview of the nEXO Detector

The nEXO detector is a monolithic, single-phase, single-sided TPC with 5 tonnes of LXe, 90% enriched in the isotope ^{136}Xe [3]. The lateral inward-facing surface of the detector will be lined with $\sim 46\,000$ ($1\text{ cm}\times 1\text{ cm}$) vacuum-ultraviolet (VUV) sensitive silicon photomultipliers (SiPM) to detect Xe scintillation light produced by events inside the TPC [88–90]. A uniform drift field is applied between the two endcaps of the cylindrical TPC, and field-shaping rings are used to ensure field homogeneity across the volume of the TPC. Ionization electrons produced by particle interactions within the LXe drift toward the anode, where they are collected by charge readout tiles and are used to reconstruct the event topology in a 2D projection [91].

A rendering of the nEXO experiment is shown in Figure 2.3. The TPC is submerged inside an inner vessel filled with a refrigerant to maintain LXe temperatures which is itself enclosed by the vacuum jacket of the outer vessel. This assembly is placed within a large tank filled with ultra-pure water to shield the detector from background radiation emitted from the cavern walls and surrounding infrastructure. The tank is instrumented with 125 photomultiplier tubes (PMT) to act as muon veto detector [92].

The nEXO detector is planned to be installed in the Cryopit experimental hall at SNOLAB, located approximately two kilometers underground. The underground setting is essential for reducing the background muon flux, lowering it from roughly $170\,\mu/(\text{m}^2\text{s})$ at

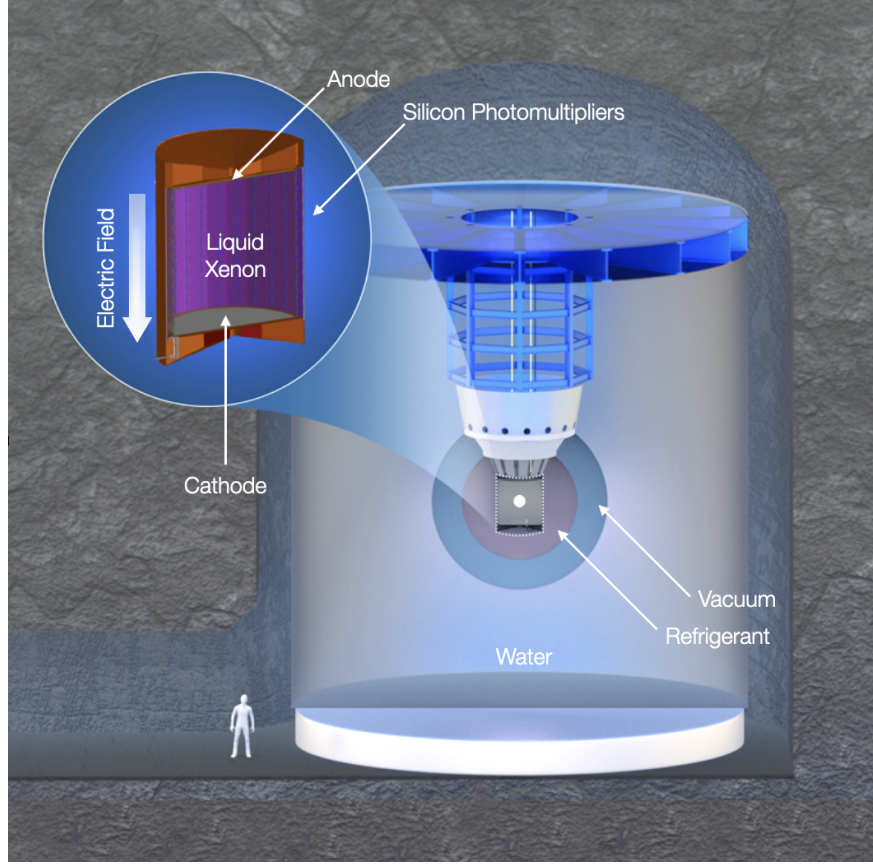


Figure 2.3: An artist rendering of the nEXO experiment shown in the SNOLAB Cryopit. Image sourced from [95].

the surface to around $3.3 \times 10^{-6} \mu/(\text{m}^2\text{s})$ at SNOLAB [93, 94].

nEXO builds upon the work of EXO-200, with the goal to utilize the scalability of the LXe TPC technology to build a tonne-scale experiment with a projected sensitivity to $0\nu\beta\beta$ of 1.35×10^{28} years [5]. Figure 2.4 shows the projected nEXO sensitivity to $0\nu\beta\beta$ half-life as a function of livetime, along with the corresponding limit of 10 meV on the effective Majorana neutrino mass after 10 years of operation.

nEXO employs a multi-parameter analysis framework that uses the reconstructed

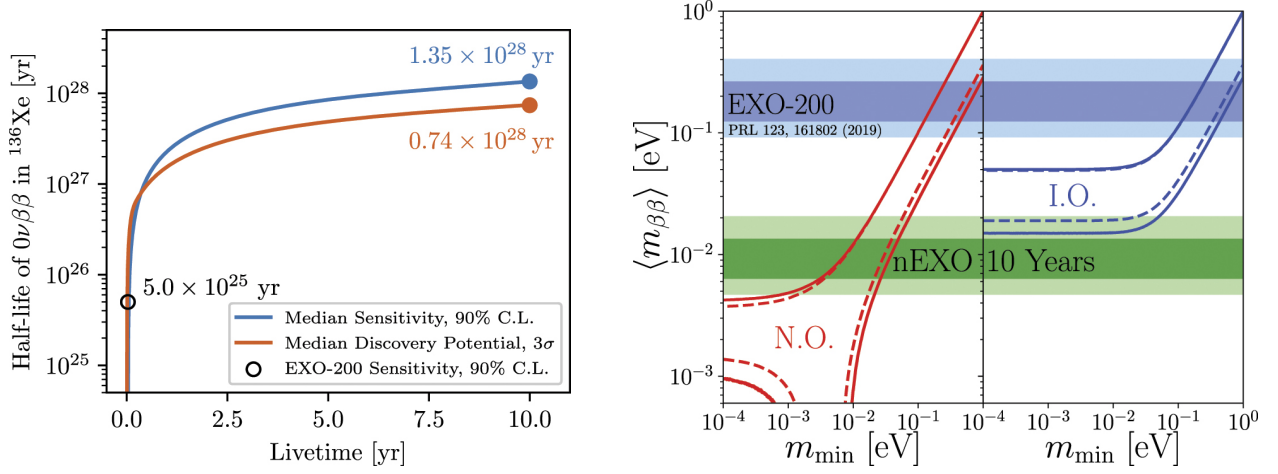


Figure 2.4: Expected sensitivity of the nEXO experiment. (Left) The projected sensitivity of nEXO as a function of livetime compared with the previous limit set by EXO-200. (Right) The effective Majorana neutrino mass as function of lightest neutrino mass. Through 10 years of data collection, the nEXO experiment aims to completely probe the inverted hierarchy of neutrino mass to reach absolute neutrino mass in the 10 meV range. Figures reproduced from [5].

energy of an event with a deep neural network (DNN)-based topology classification score¹ and the distance of the event relative to the nearest detector component inside the LXe. Figure 2.5 shows a toy dataset from simulating the nEXO detector response equivalent to 10 years of data collection for a hypothetical $0\nu\beta\beta$ half-life of 0.74×10^{28} years. The energy spectrum in Figure 2.5(c) is produced using SS-like events (DNN > 0.85), as $0\nu\beta\beta$ events are primarily SS in nature, thus excluding MS events such as Compton-scattered γ s. Additionally, only events in the fiducial volume (inner 2000 kg) are considered. This approach leverages the self-shielding property of LXe along with the detector’s energy

¹i.e. assign a DNN score based on whether an event is a SS or MS event.

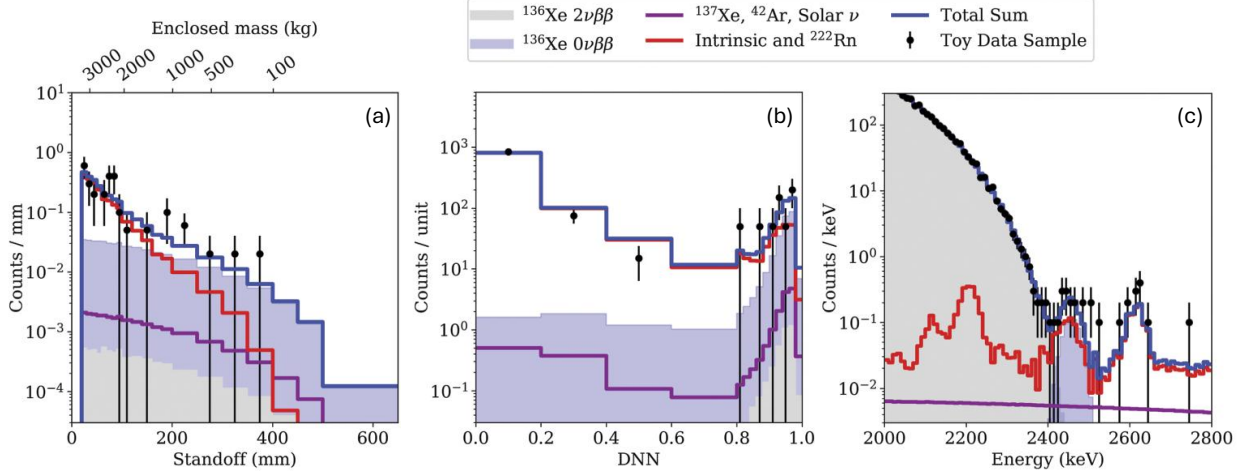


Figure 2.5: Toy dataset from nEXO simulations showing data equivalent to a 10-year livetime for a $0\nu\beta\beta$ half-life of 0.74×10^{28} years. The analysis of simulated events integrates (a) the position of events from the TPC walls (standoff distance) and (b) event topology (DNN score) to differentiate $0\nu\beta\beta$ from the major sources of backgrounds. (c) The final energy spectrum populated with events with a DNN score > 0.85 and located within the inner 2000 kg fiducial volume. Figure reproduced from [5].

resolution and event reconstruction capabilities to achieve enhanced background discrimination and signal sensitivity.

Achieving this level of sensitivity also relies on several design improvements, including the use of alternative low-radioactivity materials. A major contribution comes from the use of materials with lowest possible radioactive contaminants such as electroformed copper with its lower intrinsic radioactivity over commercially produced copper [96]. The latter originally contributed up to 20% of the total radioactive background budget for nEXO but was reduced to $< 1\%$ with electroformed copper [5, 7]. More recently, chemical vapor deposition (CVD)

nickel has also been investigated as another promising material for the nEXO TPC and cryostat [97]. Despite the many design and analysis improvements, a non-negligible level of residual backgrounds still limits the sensitivity of nEXO.

One powerful advantage for $0\nu\beta\beta$ experiments using Xe-based TPCs is the possibility of accessing the detector volume to probe for the presence of the barium daughter of ^{136}Xe double beta decays, a technique known as barium tagging. The idea of tagging the daughter ^{136}Ba to discriminate double beta decays from backgrounds was first proposed by M. K. Moe in 1991 as a path toward a virtually background-free experiment [98]. While the SM-allowed $2\nu\beta\beta$ remains an irreducible background with this technique, with sufficient energy resolution and precision in position reconstruction, it may be possible to suppress nearly all non-double beta decay backgrounds through Ba-tagging. In the context of nEXO, such a suppression corresponds to a factor of 2–3 increase over the baseline sensitivity limit.

Chapter 3

The Barium Tagging Technique

Barium tagging is an active background-rejection technique proposed for xenon-based $0\nu\beta\beta$ searches, in which the daughter ion produced in the decay is identified in coincidence with the event. Decay of ^{136}Xe produces a $^{136}\text{Ba}^{++}$ ion at the decay site, providing a signature that distinguishes it from radioactive backgrounds which do not yield barium. Due to the substantial gain in sensitivity offered by Ba-tagging, this technique was explored for EXO-200 [99] and is currently being pursued by several groups within the nEXO collaboration [100–102], as well as by the NEXT collaboration [103]. All approaches rely on some form of fluorescence signature to identify a single ^{136}Ba atom or ion, which has been demonstrated for the neutral atom [100], as well as for the singly [104] and doubly charged ions [105]. In situ studies to observe Ba^+ fluorescence in LXe, i.e., exciting the Ba ion at its decay location, could not confirm direct tagging as a feasible path to Ba-tagging [106]. Therefore, current focus of Ba-tagging R&D focuses on developing methods to extract and trap the ^{136}Ba for subsequent identification. Ba-tagging R&D is ongoing in multiple

modalities for neutrinoless double beta decay experiments [100–103, 106].

The implementation of Ba-tagging in a GXe detector medium is being actively pursued by the NEXT experiment, which searches for $0\nu\beta\beta$ using a high-pressure GXe TPC [105]. In this approach, the topological reconstruction capability of the gas TPC is complemented by an independent, event-by-event confirmation of the decay through identification of the daughter barium ion. The NEXT Ba-tagging strategy is centered around single-molecule fluorescence imaging (SMFI), in which the $^{136}\text{Ba}^{++}$ ion produced at the decay site is captured by specially designed molecular chemosensors deposited on a surface or probe. Upon binding to the barium dication, these chemosensors undergo a change in their fluorescence properties, enabling the optical detection of a single ion. This method leverages the relatively long diffusion length and lower density of the gas phase, which facilitate ion transport to the sensing surface, while ongoing R&D focuses on improving capture efficiency, selectivity against other ions, and characterizing various chemosensors for performance and robustness under high-pressure xenon conditions [103, 107, 108].

In LXe, it is expected that the $^{136}\text{Ba}^{++}$ daughter will quickly gain an electron from ^{136}Xe due to higher electron affinity (10 eV) than the LXe band-gap energy (9.22 eV) [109, 110]. ^{136}Ba will then continue to remain in its first excited state as Ba^+ due to its lower electron affinity and can be identified using laser fluorescence spectroscopy [104]. There are two Ba-tagging schemes that are currently being developed as potential future upgrade path for the nEXO experiment.

The first scheme involves the use of a cryogenic probe (or cryoprobe) that is inserted into the TPC, and positioned at the location of a candidate event that has the correct topology and energy expected from a $0\nu\beta\beta$ event. The position reconstruction performance in nEXO is expected to reach sub-centimeter precision in all three dimensions, with spatial resolution better than the 6 mm pitch of the charge readout strips [5]. Another important consideration is that the $^{136}\text{Ba}^+$ ion continues to drift under the influence of the electric field following the decay of ^{136}Xe . As a result, the target position of the cryoprobe must be corrected based on the drift velocity of the ion. This effect is informed by mobility studies of $^{218}\text{Po}^+$ and alkaline-earth ions in LXe [111, 112]. Once the cryoprobe reaches the predicted location, its tip, equipped with a sapphire window, is cooled to a temperature below the freezing point of xenon. This locally solidifies the surrounding LXe, trapping the Ba ion within the resulting solid xenon (SXe). The cryoprobe is then retracted from the TPC and the SXe is scanned using laser-induced fluorescence to verify the presence of a Ba atom [100]. The imaging of trapped Ba atoms and Ba^+ ions is currently under active study, with a focus on characterizing different Ba-related vacancy sites in the SXe matrix, investigating the photobleaching effects observed predominantly in higher-order vacancy configurations, and exploring annealing techniques to recover lost fluorescence [113].

The second scheme employs a capillary to extract $^{136}\text{Ba}^+$ along with a small amount of LXe from the TPC. Similar to the cryoprobe approach, the capillary is inserted into the TPC and positioned at the location of a candidate event. Once in place, some amount of LXe

containing the $^{136}\text{Ba}^+$ ion is extracted. The LXe is converted to gas via a heated section of the capillary and injected into an RF funnel, where the $^{136}\text{Ba}^+$ ion is separated from GXe. The ion is then transferred to an LPT, where it is trapped to be identified through laser fluorescence spectroscopy. Following identification, the $^{136}\text{Ba}^+$ ion is ejected into an MRTOF-MS for determination of its mass. Figure 3.1 illustrates the overall capillary-RF scheme for Ba-tagging. The development of the various components that make up the capillary-RF scheme of Ba-tagging is explained in this section.

3.1 Laser Fluorescence Spectroscopy

Some of the earliest work on imaging single ions in ion traps involved the use Ba [114]. The scheme for identifying Ba ions has since been developed and optimized for identifying a single Ba ion in buffer-gas cooled ion traps [104, 115]. The $^{136}\text{Ba}^+$ electronic structure resembles Xe with an additional 6S-electron. The key transitions involved in the fluorescence spectroscopy measurement are between the ground state $6^2\text{S}_{1/2}$, the excited state $6^2\text{P}_{1/2}$ and meta-stable state $5^2\text{D}_{3/2}$ levels as shown in Figure 3.2a. A combination of two lasers with wavelengths $(\lambda_1, \lambda_2) \approx (493.5, 649.9)$ nm is used to excite the Ba^+ to $6^2\text{P}_{1/2}$ state, enabling fluorescence detection while preventing trapping in the meta-stable $5^2\text{D}_{3/2}$ state. The fluorescence scheme was studied using a buffer-gas cooled linear Paul trap to localize and detect Ba^+ ions [115]. Fluorescence measured from the trapped Ba ions is shown in Figure 3.2b. The discrete changes in fluorescence rate over time correspond to individual

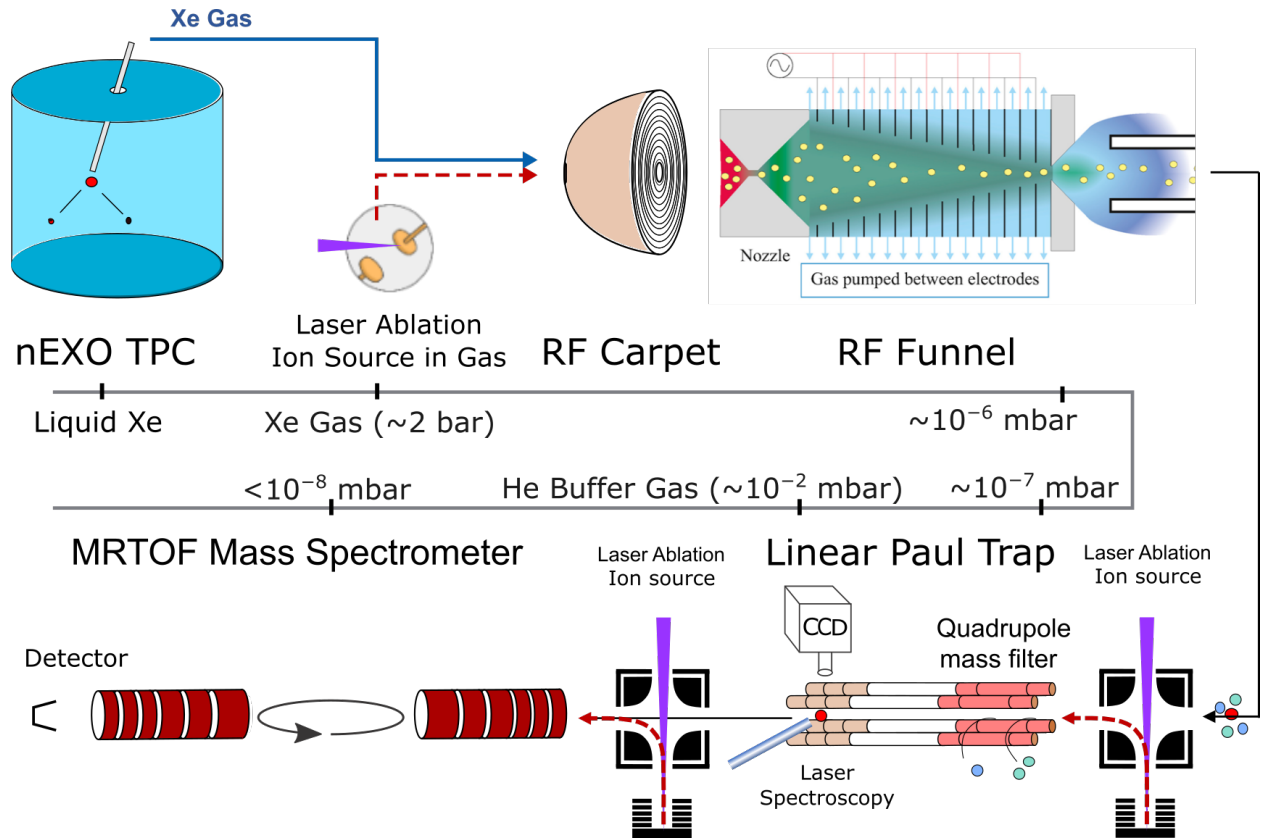
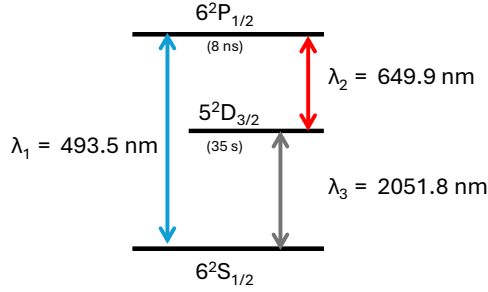
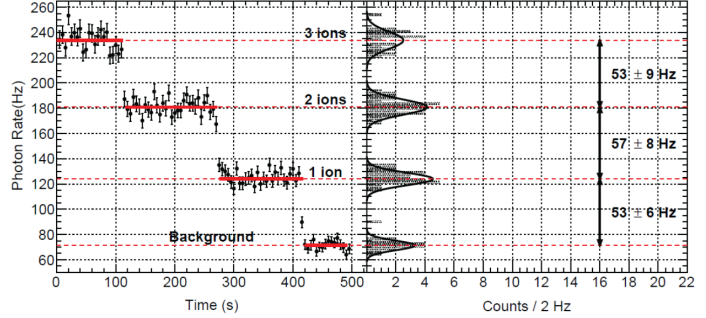


Figure 3.1: Schematic of the capillary-RF Ba-tagging scheme. The various subsystems are shown, beginning with the capillary used to extract the Ba ion along with some amount of LXe from the TPC which then undergoes a phase transition to GXe. To assist with the transfer of ion from the capillary, an RF carpet has been proposed. From the RF carpet, the ion and GXe enter the RF funnel. The ion is then separated from the accompanying GXe by the RF funnel and transferred to the LPT, where it is trapped and identified via laser fluorescence spectroscopy. An MRTOF-MS is included to measure the mass of the Ba ion after identification and to enable systematic studies. In the present work, no laser fluorescence detection was implemented.

ions leaving the trap, demonstrating the ability to resolve and identify single ions. The fluorescence scheme described here will be integrated with the LPT in the capillary-RF



(a) Ba^+ electronic structure and laser fluorescence scheme.



(b) Fluorescence measurement of trapped Ba^+ ions in a buffer-gas filled linear Paul trap. Taken from [115].

Figure 3.2: Laser fluorescence spectroscopy for Ba-tagging. Ions are stored in a buffer-gas filled Paul trap and exposed to 493 nm and 649 nm lasers. The photon rate from Ba fluorescence shown here was measured using a PMT and averaged over a period of 5 s.

scheme to allow for the identification of Ba ion extracted from GXe using the RF funnel [116].

3.2 Capillary-Based Ion Extraction Demonstrator

A demonstrator for ion extraction from a LXe volume through a capillary was developed at Carleton University [6]. The design for the capillary probe demonstrator includes a stainless steel capillary, with an outer diameter of 0.508 mm and an inner diameter of 0.2 mm, encased in a polyether ether ketone (PEEK) rod for rigidity. A pressure differential is used to extract around 1 cm^3 volume of LXe from near the probe tip. The laminar flow of LXe entrains the Ba ion from within a cylindrical volume approximately 1 cm in length and 1 cm in diameter immediately upstream of the probe tip and subsequently transports it out of the TPC [6]. A section of the capillary, outside the TPC is heated to convert the extracted LXe to GXe,

which is then supplied to the RF funnel. The probe is mounted on a wobble stick¹ and is positioned using a custom displacement device equipped with three sets of stepper motors for x-y positioning and insertion control. A test setup for the displacement device was developed and used to demonstrate the probe positioning with a precision of 0.1 mm in under 15 s [117].

COMSOL [118] simulations of the capillary probe and ion motion in LXe were used to define the LXe flow rate of 0.5 g/s and extraction time of 30 s, required to collect a Ba ion from within a 1 cm³ volume from the probe tip [6]. These simulations further indicated that the TPC drift field must be turned off during extraction to ensure sufficient collection efficiency. Hence, once the event vertex is identified, the TPC drift field will be ramped down before the capillary probe is inserted to perform the extraction.

Using the nEXO TPC length L , drift field E , and using a conservative value of $R = 100$ V/s for ramp rate, the time for ramp-down of the drift field can be calculated as follows:

$$\begin{aligned} L &= 118.3 \text{ cm}, E = 500 \text{ V/cm}, R = 100 \text{ V/s}; \\ V &= E \times L = 500 \frac{\text{V}}{\text{cm}} \times 118.3 \text{ cm} = 59.15 \text{ kV}; \\ t_{\text{down}} &= \frac{V}{R} = \frac{59.15 \text{ kV}}{100 \text{ V/s}} \approx 10 \text{ min.} \end{aligned}$$

The exact effects of this ramp-down on the drift of the Ba ion have yet to be studied in detail, and this work will likely resume once the design of the drift field electronics for nEXO is finalized. Ramp-up, by comparison, is expected to take longer, with ramp rates of 20–

¹WS40 wobble stick, UHV Design.

100 V/s [119]. Ba ion and LXe extraction via the capillary probe is expected to take on the order of one to a few minutes. Altogether, since a $0\nu\beta\beta$ -like event is expected roughly once per day based on background modeling and detector simulations [5], the total dead-time to nEXO operation from Ba-tagging is expected to be $\approx 10\text{--}60$ min/day, dominated by the time required to cycle the drift field.

The concept of ion transport via a capillary was characterized by transporting and detecting ^{218}Po ions via Ar gas transport. Ar was chosen as a surrogate for this feasibility study due to its availability and cost. ^{222}Rn was first introduced into gaseous argon (GAr) in a source chamber and allowed to decay for several hours to accumulate ^{218}Po ions. Through a pressure differential, the GAr was transported through the capillary, carrying ^{218}Po ions from the source chamber to the detector chamber. ^{218}Po ions are identified via the characteristic energy of the emitted α particles from their subsequent decay, measured with a passivated, implanted, planar silicon (PIPS) detector. The initial results show successful transfer of ions through the capillary, though further testing using GXe and eventually LXe is required to obtain a quantitative estimate of the transport efficiency [120].

3.3 Ion Isolation and Identification

The $^{136}\text{Ba}^+$ ion extracted through the capillary is expected to be in GXe pressures above 1 bar, where the ion's motion is dominated by frequent collisions with the gas. To overcome

this, the ion is extracted from this high-pressure environment to a vacuum region, where its motion can be precisely controlled for trapping and spectroscopy using well-established methods. This extraction typically requires several stages of differential pumping. However, each pumping stage reduces the overall ion transport efficiency. To mitigate this, an RF funnel is employed as part of the Ba-tagging scheme to efficiently guide the Ba ion from high-pressure GXe into a high-vacuum environment [121].

The RF funnel discussed in this work was originally developed for Ba-tagging in gas-phase xenon detectors [122]. It has since been adapted to operate in conjunction with the capillary probe for ion extraction from liquid xenon detectors such as nEXO. The RF funnel was studied for ion extraction and transport using radioactive sources such as a ^{148}Gd -driven Ba-ion source [123] and a ^{252}Cf source to successfully demonstrated extraction of ions from GXe [121]. Figure 3.3 shows a subsequent study of the extracted ions using a commercial linear quadrupole ion trap (LTQ)² that was unable to identify any Ba ions and revealed the presence of various molecular species of Xe in the extracted ions that dominated the observed signal, ionized by the radioactive ion source.

To facilitate the filtering of ions from the RF funnel and support systematic studies of the extracted ion, the Ba-tagging scheme was extended to replace the LTQ with a more sensitive LPT and a custom built MRTOF-MS [101, 125]. A quadrupole mass filter (QMF), shown in Figure 3.1, is used to filter ions far from the target mass exiting the RF funnel

²Thermo Finnigan LTQ XL, Thermo Fisher Scientific, Waltham, MA, USA.

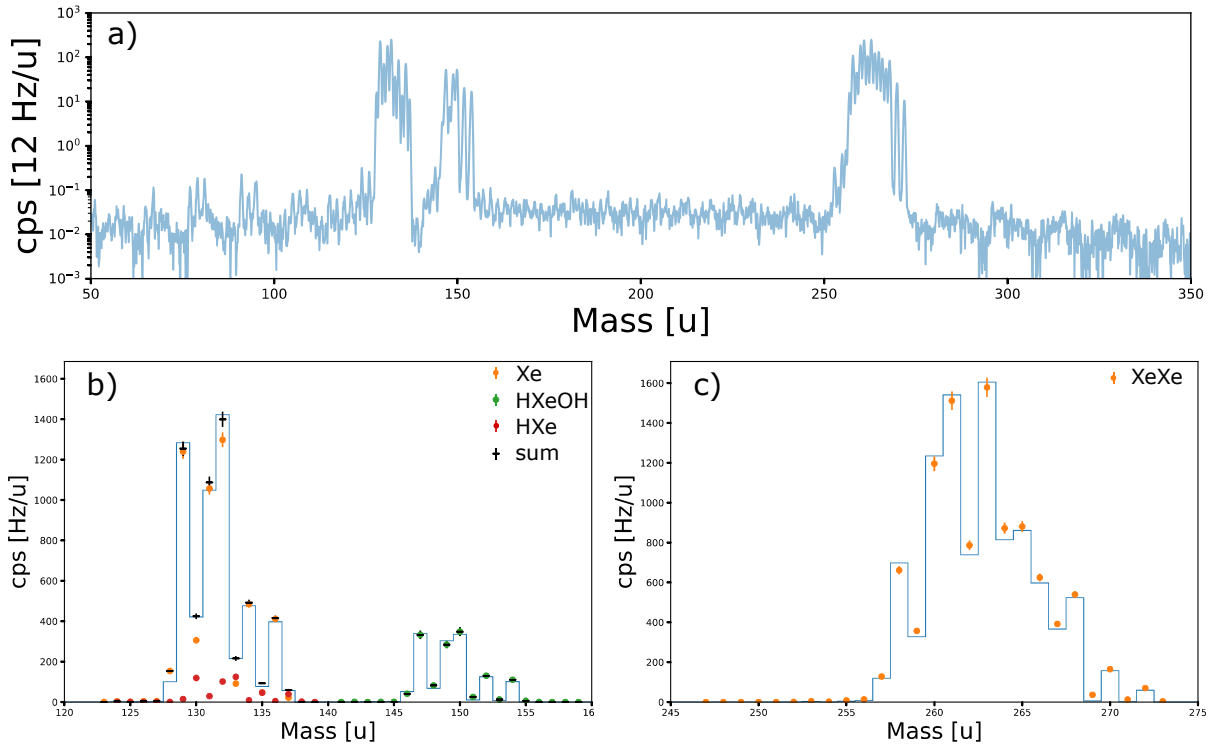


Figure 3.3: Ionized species extracted from 2.1 bar GXe using the RF funnel, recorded with the LTQ. (a) The m/q spectrum measured at 2.1 bar GXe pressure. (b) Enlarged view of the lower mass peaks showing the presence of atomic and molecular Xe ions in the region of interest. (c) Enlarged view of the higher mass peak showing a Xe dimer signal centered at 262 u (twice the average Xe atomic mass, 131 u). Figure reproduced from [124].

based on their mass-to-charge ratios. The selected ions are then cooled and stored in an ion trap where Ba ions can be identified using laser fluorescence spectroscopy, once implemented. This ion trap doubles as an ion buncher, used to supply ion bunches to the MRTOF-MS for mass-to-charge ratio measurements. The combined system comprising the RF funnel, the LPT, and the MRTOF-MS is currently being used to demonstrate ion extraction from GXe.

The details of these three subsystems and their operation are discussed in Chapters 6 and 7.

Lastly, an RF carpet is planned to be implemented with the Ba-tagging system upstream from the RF funnel as depicted in Figure 3.1. Its role is to improve the ion transfer efficiency between the capillary and the RF funnel. GXe from the capillary probe will be supplied to the RF carpet chamber, where a drift field directs the Ba ion towards the RF carpet. The RF carpet consists of concentric ring shaped electrodes that are supplied with an RF potential to levitate the ion at a distance from the RF carpet surface. In the ion-surfing mode of operation, a secondary high-frequency potential is superimposed onto the primary RF field to drive the ion toward the center of the RF carpet [126]. From there, the ion is efficiently carried by the flowing GXe into the RF funnel. A similar application of the RF carpet is being explored for the NEXT experiment with their SMFI technique [127].

3.4 In situ Ion Source Development

The developments discussed so far aim to design and optimize various components of the Ba-tagging scheme to achieve a high tagging efficiency. While individual efficiencies matter, the efficiency of the entire scheme put together is the main metric that will be used to demonstrate the usefulness of this technique. To this end, a test setup for an accelerator driven in-LXe Ba ion source is being developed at the ISAC-II experimental facility at TRIUMF [128] to be eventually used to demonstrate and calibrate the complete Ba-tagging system.

Figure 3.4 shows a CAD model rendering of the setup consisting of three main sections: an injection chamber housing a LXe vessel, a measurement chamber equipped with Ge detector, and an extraction probe that moves ions between the two chambers. A ^{139}Cs ion beam [$T_{1/2} = 9.27(5) \text{ min}$] [129] will be delivered to the LXe vessel through a $25 \mu\text{m}$

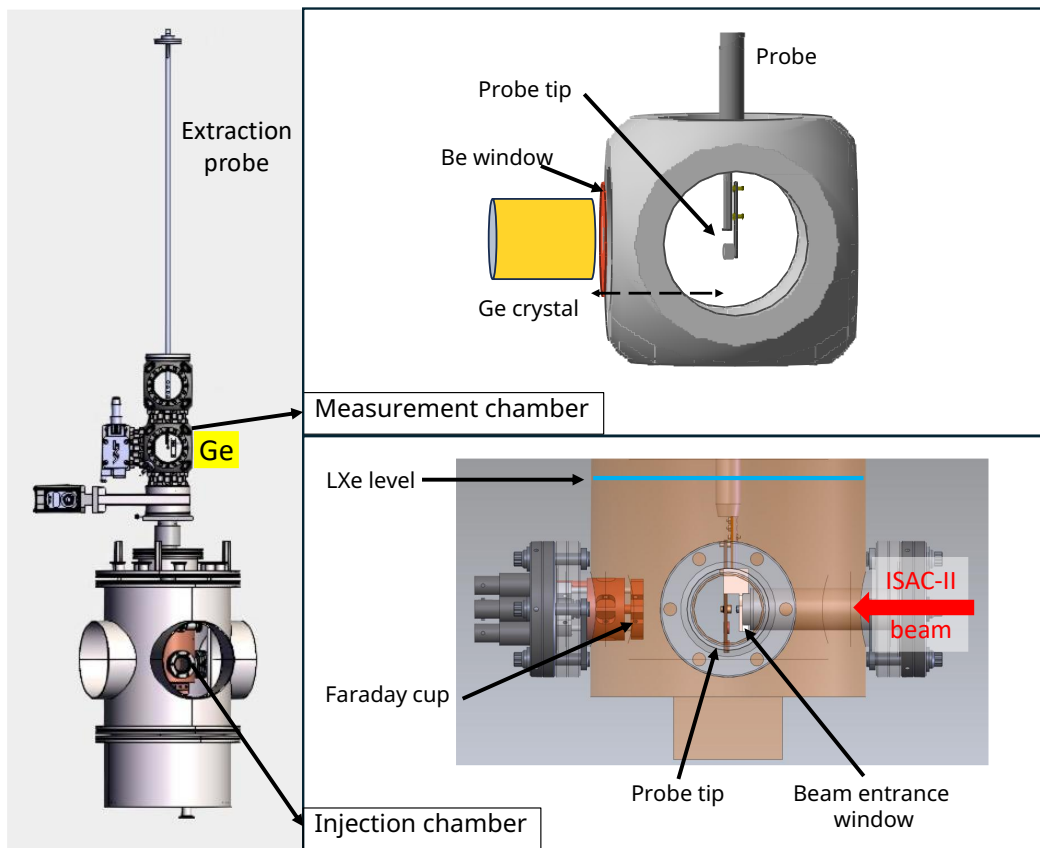


Figure 3.4: CAD model rendering of the test setup for an accelerator driven in-LXe ion source. The setup consists of three sections: an injection chamber (bottom right) housing a LXe vessel and a Be window for ion implantation, a measurement chamber (top right) equipped with a Ge detector for measuring gammas produced through the decay of ^{139}Cs and its daughter ^{139}Ba and an extraction probe for moving ions between the two chambers. Figure reproduced from [6].

Be window and will be allowed to come to rest in the LXe. The Be window is positioned near the center of the vessel through a recessed tube to deliver radioactive Cs ions near the extraction probe. ^{139}Cs and its daughter ^{139}Ba ions are collected on the probe tip by applying a bias potential [130], after which they are transferred to the detection chamber for gamma-ray spectroscopy. Detection of the gamma resulting from the decay of ^{139}Ba is used to demonstrate the successful implantation of ^{139}Cs ions. The setup has been assembled and will be commissioned and tested first with GAR to demonstrate ion beam transmission through the Be foil, and eventually with LXe. Upon successful demonstration of ion implantation, the ion source will be used to validate the capillary-RF Ba-tagging scheme and determine its overall tagging efficiency.

One of the main drivers of the scheme discussed here is the well-developed ion-handling techniques that enable precise and efficient transport and confinement of ions. Chapter 4 provides an overview of the theoretical principles governing the operation of RF-based components, including ion guides, traps, and associated ion optics.

Chapter 4

Ion Transport and Time-of-Flight Principles

Charged particle optics is analogous to conventional ray optics, but instead of manipulating photons, the objects of control are charged particles, and electromagnetic fields are analogous to dielectric media. Proper electrode and magnet geometries enable focusing and steering of ions analogous to optical elements such as lenses and mirrors. Here, a charged particle can be anything ranging from the smallest charged particles, electron and positron, to large polymer-chains. This chapter outlines a selection of apparatuses commonly used to manipulate ion motion, with an emphasis on components relevant to the Ba-tagging setup discussed later in Chapter 5.

4.1 Fundamentals of Ion Optics

Ion beams inherently possess finite transverse emittance and angular divergence. As they propagate, mutual electrostatic repulsion can further cause the beam to diverge, an effect typically referred to as the space-charge effect, requiring external focusing forces to counteract this expansion. To preserve beam quality and transmission efficiency, electrostatic focusing elements, such as apertures and electrostatic lenses, are employed to compensate for this divergence.

Figure 4.1 presents the scenario of an ion passing through an aperture biased to a potential V_{ap} measured relative to the ion source potential. For a distance r relative to the aperture center and ϕ defined as the inclination of the ion's trajectory with respect to the z-axis, the equation of motion of the ion can be expressed in matrix formulation as [131]:

$$\begin{pmatrix} r' \\ \phi' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{E_1 - E_2}{4V_{\text{ap}}} & 1 \end{pmatrix} \begin{pmatrix} r \\ \phi \end{pmatrix}. \quad (4.1)$$

Here, E_1 and E_2 are the electric fields experienced by the ion before and after the aperture, respectively, and r' and ϕ' denote its position and inclination after crossing the aperture. On comparing with the transfer matrix for an optical lens, one can conclude that the focal length of the aperture is $f = 4V_{\text{ap}}/(E_2 - E_1)$. Depending on the values for V_{ap} , E_1 and E_2 the focal length can take positive or negative values determining the extent of its converging

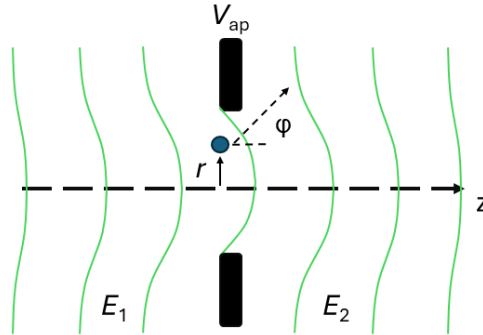


Figure 4.1: Schematic of a charged particle passing through an aperture biased to a potential V_{ap} relative to the ion source. Here, the equipotential lines, shown in green, distort due to the field discontinuity across the aperture, leading to focusing or defocusing of the ion trajectory, described by its position r and angle ϕ .

or diverging power.

A popular configuration of lenses is an Einzel lens [132]. It uses three sets of lenses where the first and third lenses are typically held at the same potential (V_1) different from the second, or middle, electrode (V_2). One can easily develop the transfer matrix for this configuration by taking a product of three apertures combined with ion propagation matrices for drift spaces in between the apertures. Due to this configuration, ions are first decelerated and then accelerated (or vice-versa depending on the values of V_1 and V_2) with the overall result being the focusing of ions. Figure 4.2 shows a sectional view and potential energy view of an Einzel lens generated using SIMION [133]. In the example, 200 eV ions are generated uniformly over a circular region about the beam axis, and the bias potentials $(V_1, V_2) = (0, 100)$ V are applied to the cylindrical electrodes.

Complementary to electrostatic lenses, RF ion guides offer an alternative approach for

the continuous confinement of ions, particular in applications involving elevated gas pressures or the presence of buffer gas. The principles and operation of RF ion guides are discussed in the following section.

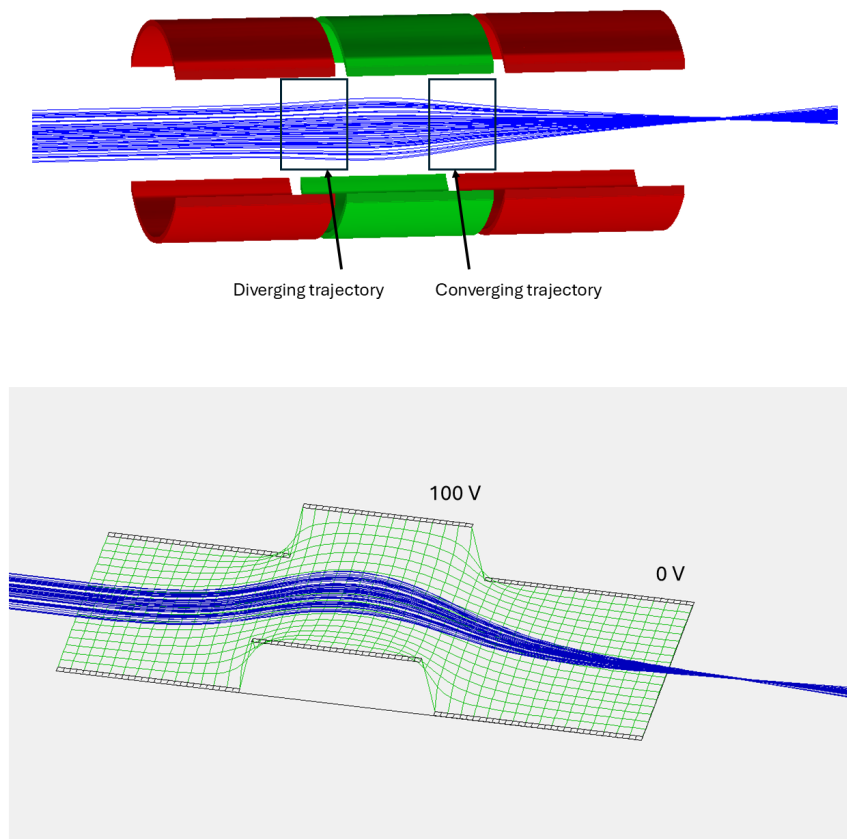


Figure 4.2: SIMION simulation of an Einzel lens. (Top) Trajectories of 200 eV ions, generated uniformly over a circular region about the beam axis, passing through the Einzel lens and converging downstream. The electrode (shown in green) is biased to 100 V. (Bottom) Corresponding electrostatic potential energy distribution.

4.2 Radio-Frequency Ion Guides

Earnshaw's theorem states that a charged particle cannot be held in a stable equilibrium by static electric forces alone because there are no local minima in a static electric potential [134].

While this always holds true, it is possible to create a pseudo minima or a psuedo potential well through the use of alternating fields.

Let $\bar{F} = F_x \hat{x} + F_y \hat{y}$ be a radial restoring force applied to confine the motion of an ion moving along the z-axis and let $\bar{F}$ be proportional to distance of the ion from the axis:

$$F_x = -k_x x = Q E_x, \quad F_y = -k_y y = Q E_y, \quad (4.2)$$

where (k_x, k_y) are proportionality constants, (E_x, E_y) are the magnitude of electric field along x and y axes and Q is the charge of the ion. A general expression for the electric potential corresponding to such a linear restoring field can be written as:

$$\Phi = (U + V \cos \Omega t) \left(\frac{x^2 - y^2}{r_o^2} \right). \quad (4.3)$$

Here, the potential Φ depends on the transverse position given by (x, y) and time t . U is a constant DC potential, V is the amplitude of the time varying potential with frequency $f = \Omega/2\pi$ and r_o is a constant. A quadrupole arrangement of hyperbolic-shaped electrodes can be used to create such an electric potential [135]. Quadrupoles are the simplest possible

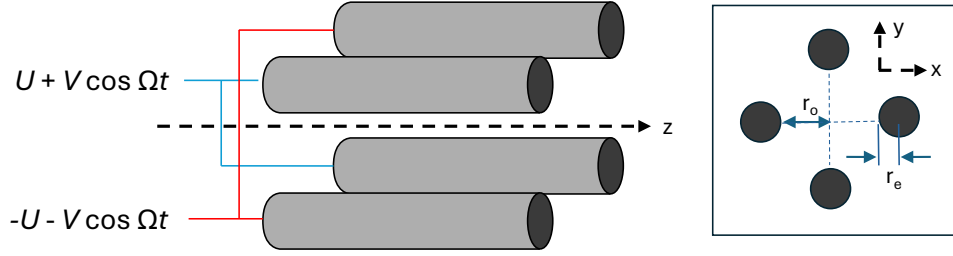


Figure 4.3: Schematic of a quadrupole ion guide. (Left) Potentials applied to the quadrupole electrodes. (Right) Geometry of the electrodes, showing rods of radius r_e evenly spaced at a distance r_o from the axis.

form of an RF ion guide. A quadrupole consists of four parallel electrodes, symmetrically arranged about the axis at a distance of r_o . To simplify electrode fabrication, hyperbolic electrodes can be substituted with circular ones, which closely approximate the electric field near the axis. Figure 4.3 shows a schematic of a quadrupole ion guide with the potential Φ applied to the electrodes such that adjacent electrodes have opposite polarities. The optimal approximation occurs at the magic ratio, which is when the radius of curvature (r_e) of the circular electrode satisfies $r_e \approx 1.14511 r_o$ [136]. For an ion of mass m and charge Q in a quadrupole field, the equations of motion can be expressed as follows:

$$\frac{d^2x}{dt^2} + \left(\frac{Q}{m}\right)(U + V \cos \Omega t) \left(\frac{2x}{r_o^2}\right) = 0, \quad (4.4)$$

$$\frac{d^2y}{dt^2} - \left(\frac{Q}{m}\right)(U + V \cos \Omega t) \left(\frac{2y}{r_o^2}\right) = 0. \quad (4.5)$$

The form of Equation 4.4 and 4.5 can be recast in the form of the Mathieu's equation [135]:

$$\frac{d^2x}{d\epsilon^2} + (a_x - 2q_x \cos 2\epsilon)x = 0, \quad (4.6)$$

$$\frac{d^2y}{d\epsilon^2} + (a_y - 2q_y \cos 2\epsilon)y = 0, \quad (4.7)$$

$$a_x = -a_y = \frac{8QU}{mr_o^2\Omega^2}, \quad q_x = -q_y = \frac{4QV}{mr_o^2\Omega^2}, \quad \epsilon = \frac{\Omega t}{2}. \quad (4.8)$$

Equations 4.6 and 4.7 have convergent solutions for x and y , respectively, for specific values of the parameters (a, q) . The lines in Figure 4.4 indicate the boundaries of the regions with convergent solutions for the corresponding values of (a_x, q_x) and (a_y, q_y) . The region highlighted in green corresponds to values of (a, q) where Equations 4.4 and 4.5 simultaneously have convergent values of (x, y) , which translates to a stable ion trajectory in the quadrupole ion guide. For this reason, (a, q) are referred to as stability (or trajectory) parameters. The theory of RF ion guides can be extended in increments of two to a sextupole ion guide (SPIG), octopole ion guide, and so on. The higher number of poles helps create a more homogeneous potential at the center, with steeper fields near the electrodes, therefore enabling the transport of larger ion beam currents [137]. Apparatuses such as the RF funnel and RF carpet, discussed in Chapter 2, similarly exploit the alternating converging-diverging nature of the RF potential to stabilize ion motion in gaseous environments [126, 138].

Ions exhibit oscillatory motion in a quadrupole, with a micromotion determined by the

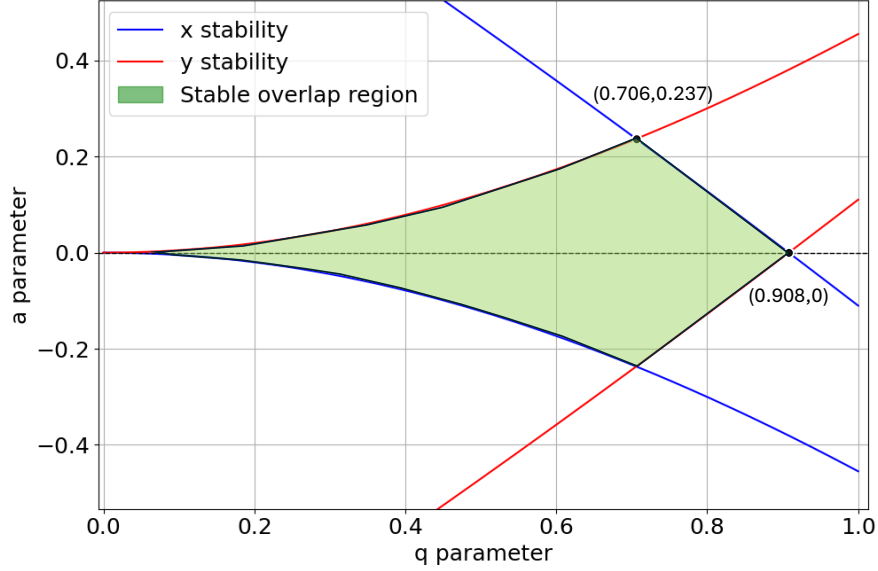


Figure 4.4: The stability regions for ion motion in a quadrupole ion guide. The values for (a, q) in the overlapping region highlighted in green simultaneously provide stable ion trajectories along both axes.

RF frequency and macromotion governed by the depth of the pseudopotential well. The pseudopotential well created by the quadrupole can be expressed as:

$$\bar{D}_x = U + \frac{|q_x|V}{4}, \quad \bar{D}_y = -U + \frac{|q_y|V}{4}, \quad (4.9)$$

where D_x and D_y are the depths along the x and y axes. The opposite sign for U along the two axis results in enhancement of trapping along a particular axis at the expense of the perpendicular axis. For a select RF amplitude V , the instability introduced by U can be used to selectively allow ions of a particular mass to charge ratio (m/Q) to traverse. This

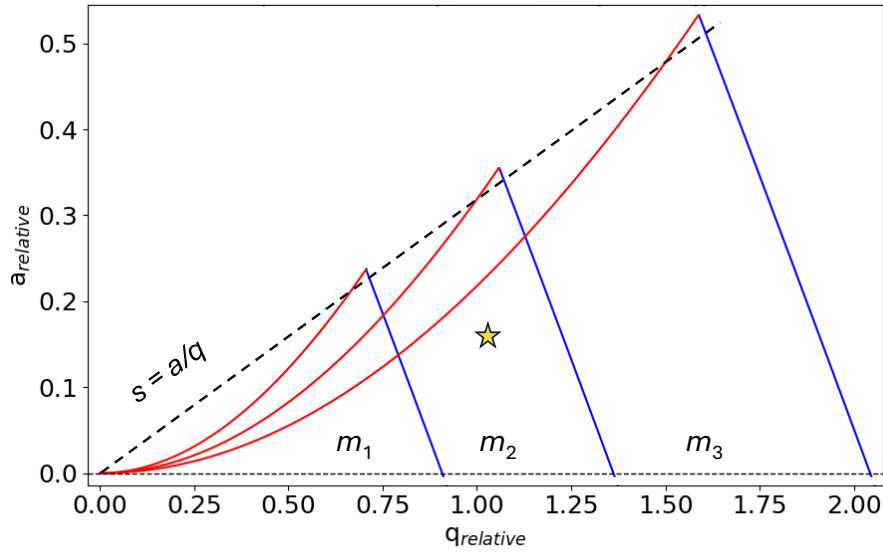


Figure 4.5: Plot of the stability region in the first quadrant for three ions with masses m_1 , m_2 , m_3 , where, $m_2/m_1 = m_3/m_2 = 1.5$. By operating the quadrupole with (a, q) values highlighted with $\star$, the ion with mass m_1 can be filtered out while ions of masses m_2 and m_3 traverse. Similarly, one can perform mass measurements on an ion beam by scanning across the stability region along the dashed line of slope s .

is the principle behind the operation of a quadrupole mass filter (QMF). Figure 4.5 shows this with the example of three ions with masses in the ratio of 1 : 1.5 : 2.25 relative to the lightest ion mass m_1 . In this example, the ion mass m_1 can be filtered out by operating at the DC and RF amplitudes corresponding to the highlighted point ($\star$). Mass measurements can also be performed using a QMF by scanning the RF amplitude V along a fixed operating line, while keeping the ratio V/U constant. This results in different mass-to-charge species being transmitted at different values of V , producing a series of resolved peaks. Since the values for DC and RF amplitudes are proportional to the mass of the ion from Equation 4.8,

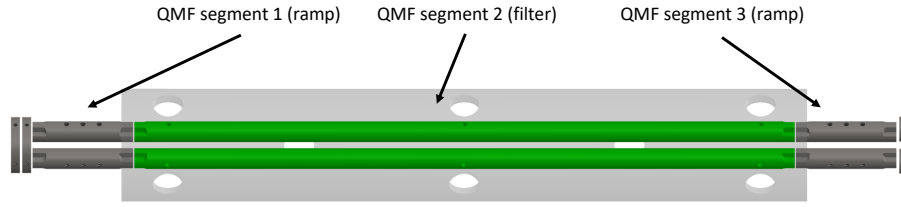


Figure 4.6: CAD rendering of the QMF used in the capillary-RF Ba-tagging scheme. The device consists of three quadrupole segments. The central segment, highlighted in green, is the longest and provides the primary mass filtering. The ramp segments on either side ensure a smooth transition of ions through the fringing fields.

the location of the ion peaks along the scan line can be used to calculate their masses. The resolving power R of the QMF can be calculated as:

$$R = \frac{m}{\Delta m} = \frac{V}{\Delta V}, \quad (4.10)$$

where ΔV is the full width at half-maximum (FWHM) of the mass peak and Δm is the smallest measurable mass difference. One of the main factors influencing the width of the mass peak is the overlap between the scan line and respective stability region. The resolving power can be increased by scanning at larger values for the slope up to a maximum value of $s = 0.237/0.706 = 0.336$ corresponding to the peak of the stability region. To operate near the peak of the stability region, the QMF used in the Ba-tagging setup is divided into three segments. Figure 4.6 shows the design, where the first and last segments act as ramp sections, while the central segment performs the mass filtering. The ramp segments provide a gradual transition for incoming ions, mitigating the effects of fringing fields. Figure 4.7

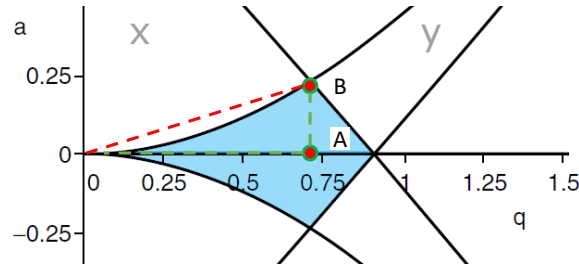


Figure 4.7: Depiction of an ion trajectory in stability space. Points A and B correspond to the operating conditions in the ramp and main segments, respectively. The ramp segments enable a smooth transition of ions between these regions.

illustrates the ion trajectory in stability space, with points A and B corresponding to the operating conditions in the ramp and main segments, respectively. Ions entering the QMF originate near the stability origin. The ramp segments are operated as ion guides, with no differential DC bias applied to their electrodes. The presence of intermediate ramp segments reduces the impact of fringing fields and improves transmission efficiency [139]. As shown in Fig. 4.7, the ramp segments allow the ions to move from the origin to point A before reaching point B in the filtering region. Without these segments, ions would transition directly from the origin to B, increasing the likelihood of loss while traversing unstable regions. A similar effect occurs at the exit of the QMF, where the ramp segment guides ions smoothly back toward stable conditions before entering the next stage of the apparatus.

An extension of the quadrupole application is its use as a linear Paul trap (LPT). In this configuration, the radial confinement provided by the quadrupole field is supplemented with an axial DC potential to achieve three-dimensional ion confinement. The potential applied

in this situation is typically an RF potential (V) coupled to a DC potential (U_t) such that:

$$\Phi_+ = U_t + V \cos \Omega t, \quad \Phi_- = U_t - V \cos \Omega t, \quad (4.11)$$

where Φ_+ and Φ_- are the two potentials supplied to the quadrupole electrodes, where U_t provides the axial trapping potential. Combining axial control of ion motion with radial confinement from the quadrupole field provides full three-dimensional control over an ion's motion. Figure 4.8 shows a side view of the LPT-buncher along with the axial potentials during the three standard phases of operation. The buncher consists of three quadrupole segments, with apertures (LA1, LA2) at the entrance and exit, respectively. Incoming ions are first allowed to accumulate in the buncher. A DC bias is applied to the electrodes to create a potential minimum at the center of the buncher. As ions lose energy through collisions with the buffer gas, they are no longer able to overcome the potential barriers on either side. Once the ions are trapped, the DC potential on LA1 is raised to prevent further ions from entering, allowing the stored ions to cool. Finally, the DC potentials on LA2 and the buncher electrodes are adjusted to create a forward electric field, ejecting the ions from the trap.

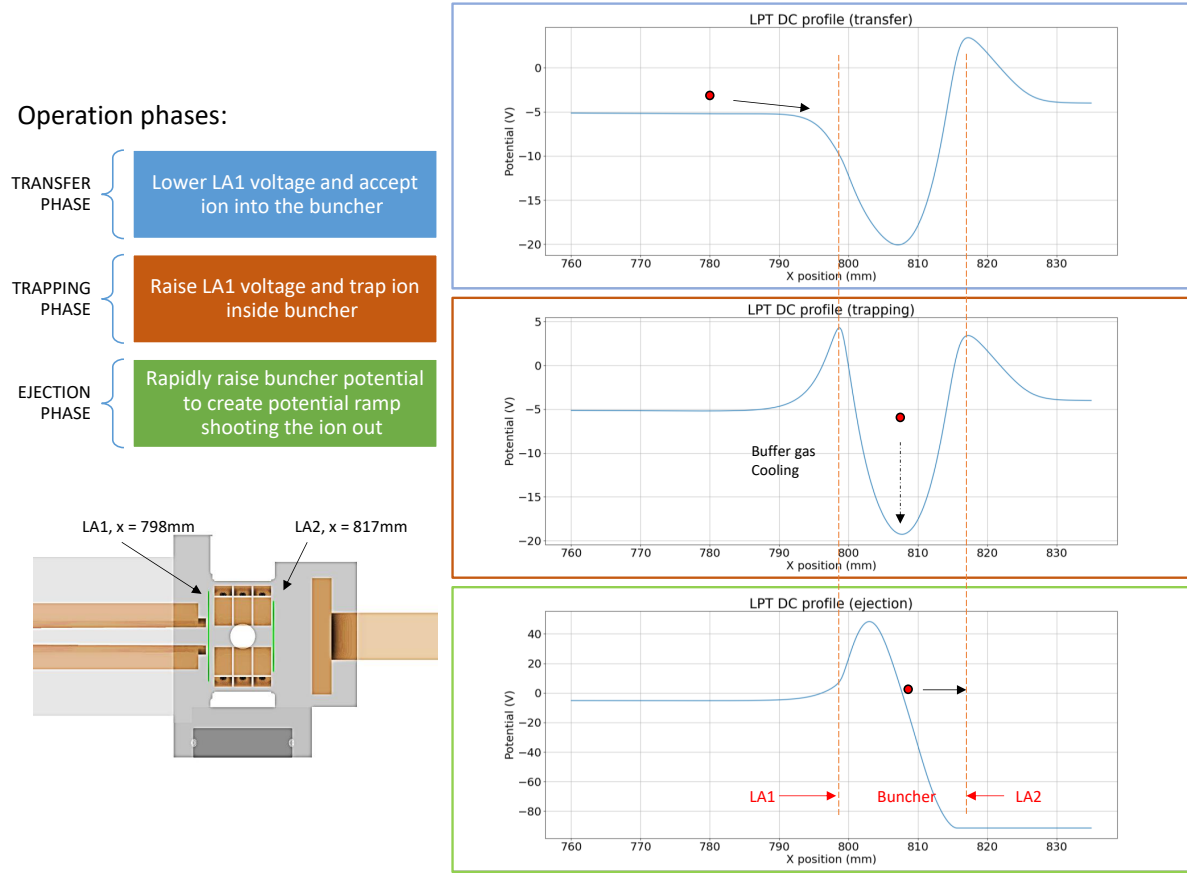


Figure 4.8: CAD model rendering of a linear Paul trap and depiction of the potential along its axis. The three phases in the operation of the ion trap are illustrated with the help of axial DC potential profiles corresponding to each phase.

4.3 Time-of-Flight and Mass Spectroscopy

For an ion of mass m and kinetic energy E traversing a distance L , in the classical non-relativistic case, the time of flight is:

$$t_{\text{TOF}} = L \sqrt{\frac{m}{2E}}. \quad (4.12)$$

The t_{TOF} of ions with the same kinetic energies depends on their mass. This is the main principle behind time-of-flight mass spectrometry [140]. The resolving power of a TOF mass spectrometer R is given by:

$$R = \frac{m}{\Delta m} = \frac{t_{\text{TOF}}}{2 \Delta t_{\text{TOF}}}, \quad (4.13)$$

where Δm is the mass difference corresponding to the smallest resolvable separation between two ions at mass m , and Δt_{TOF} is the FWHM of the mass peak.

Higher mass resolution can be achieved by either reducing Δt_{TOF} or by increasing t_{TOF} . The former is often defined by the ion source or the stability and homogeneity of electric fields and as such cannot be indefinitely reduced, while on the other hand, increasing t_{TOF} is possible by increasing the distance travelled by the ions. This can be achieved by folding the ion trajectory onto itself through successive reflections between deflectors or electrostatic mirrors.

Figure 4.9 illustrates several possible configurations of TOF spectrometers designed to maximize ion path length while minimizing the overall instrument size. Taking the example of an MRTOF-MS with a drift length of 2 m, 500 revolutions amount to a total path length of 1 km. In an MRTOF-MS, the ions are reflected over and over between two sets of electrostatic mirrors made of cylindrical-shaped lenses, similar to those shown in Figure 4.2. When the lens potentials are biased above the ion kinetic energies, the ions are reflected instead of being transmitted. Through repeated reflections and refocusing between the electrostatic mirrors, ions can be confined within the MRTOF-MS. This is illustrated in Figure 4.10,

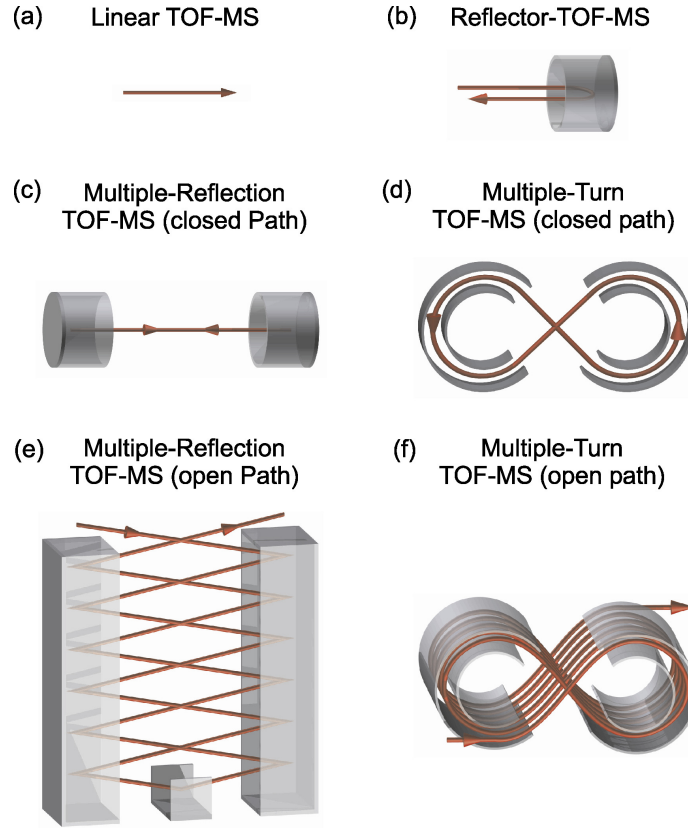


Figure 4.9: Various configurations of time of flight spectrometers. Figure reproduced from [141].

which shows the TOF spectrum of Cu ions, where the two naturally occurring isotopes become progressively separated over five revolutions in an MRTOF-MS.

As mentioned earlier, TOF measurements require ion preparation, either using an ion trap or a pulsed source to deliver well-defined ion bunches. Even for tightly bunched ions with initial time spreads as small as 1 ns, the time spread increases as the ions propagate away from the focal plane, i.e., the location along the trajectory where all ions in the bunch arrive simultaneously. The temporal spread arises because ions originate from slightly different

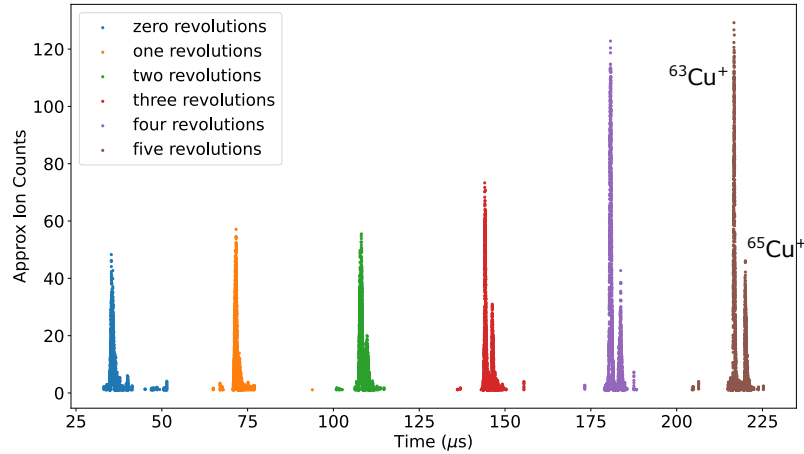


Figure 4.10: TOF spectrum of Cu ions measured with the MRTOF-MS. The two peaks corresponding to the naturally occurring isotopes of Cu become increasingly separated with successive revolutions in the MRTOF-MS. Reproduced from [125].

positions inside the trap and therefore experience unequal acceleration during extraction, causing some ions to gain more energy or start earlier than others. Thus, often either the first or the last MRTOF-MS revolution is used to refocus the ions such that the new focal plane coincides with the ion detector position as shown in Figure 4.11. This step is referred to as a time-focus shift (TFS) [142]. The remaining revolutions preserve the time focus and are in other words isochronous. This way, through finely tuned potentials, ions can be trapped for a large number of revolutions.

Mass measurements in an MRTOF-MS are performed by comparing the TOF of ions of interest to those of ions with well-known masses under identical experimental conditions [141]. The mass is then determined by relating the measured TOF of the ion of

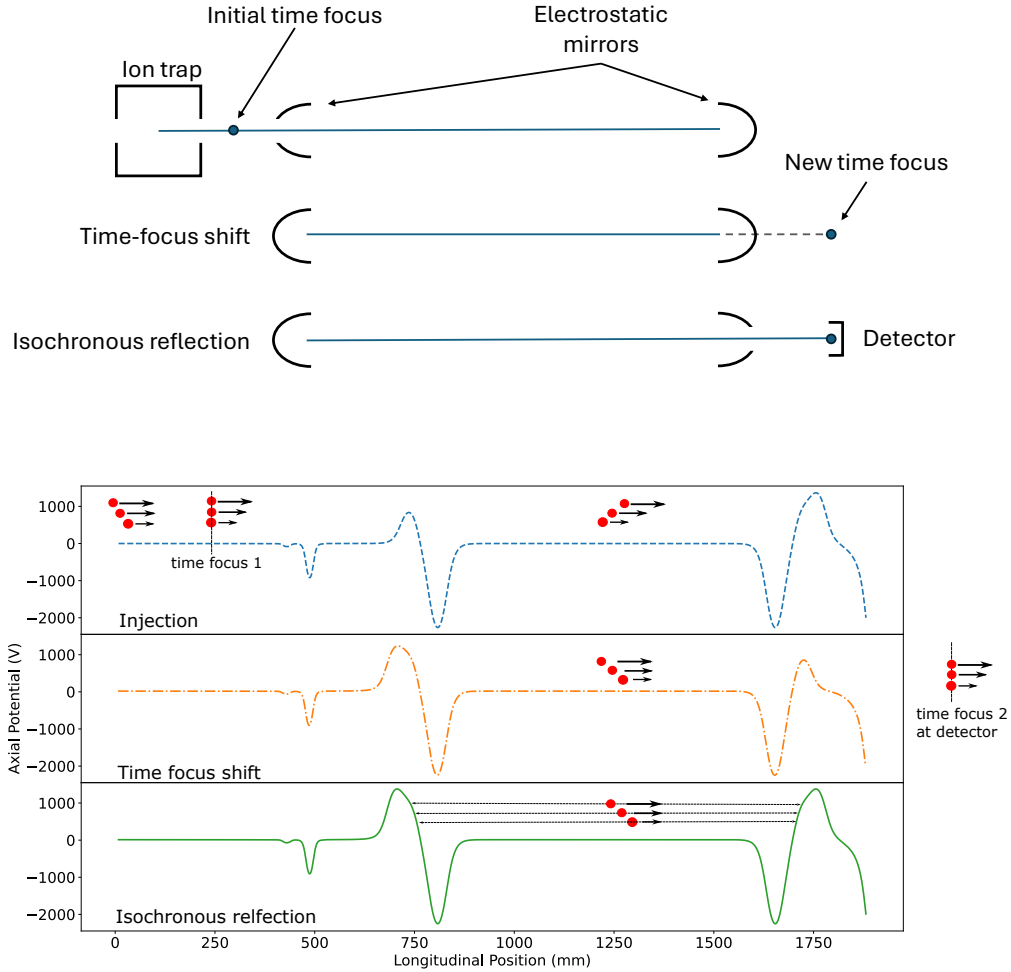


Figure 4.11: Ion bunch reflections and focusing in an MRTOF-MS. (Top) An ion bunch, supplied by a preparatory ion trap, is injected into the analyzer region, where it undergoes successive reflections between two electrostatic mirrors. To compensate for the initial time-focus position, the potential of one mirror is adjusted to refocus the ions such that the time-focus plane coincides with the detector. Once this condition is achieved, subsequent reflections preserve the time focus. (Bottom) Example of the axial potentials during operation of the MRTOF-MS, with the ion bunch represented by three red dots indicating leading, median, and lagging ions. Figure reproduced from [125].

interest to those of reference ions, typically using a calibration function of the form $t = a\sqrt{m/q} + b$, where a and b account for the effective flight path and timing offsets. Taking the example shown in Fig. 4.10, the mass and TOF of the ^{63}Cu peak can be used to determine the mass of ^{65}Cu . In practice, the calibration function may include additional correction terms, and two or more reference ions may be used to better account for drifts in timing and electrostatic potentials, enabling precise determination of the mass-to-charge ratio of unknown species.

Altogether, MRTOF-MS offers an elegant solution for achieving high mass resolution within a compact geometry. At TRIUMF's TITAN MRTOF in Canada, mass resolving power (MRP) of $R \sim 4 \times 10^5$ are routinely achieved, with measurements exceeding 6×10^5 under optimized conditions [143]. Comparable MRP have been demonstrated at other facilities, including the RIBF facility at RIKEN in Japan [144], the IGISOL facility in Finland [145], and the MRTOF-MS at GSI in Germany [146]. As a result, MRTOF-MS have become a preferred choice for precision mass measurements of short-lived isotopes and rare ions, where both high resolving power and fast measurement times are critical. An MRTOF-MS has been commissioned for the capillary-RF Ba-tagging scheme, and its operation is discussed in detail in Chapter 7.

Chapter 5

Barium Tagging Setup for Ion Extraction from Gaseous Xenon

The capillary-RF scheme discussed in Chapter 2 describes the approach being pursued to extract LXe from the nEXO TPC to probe for the presence of the Ba daughter ion. The R&D efforts to develop this scheme are divided into two main parts. The first focuses on the development of the capillary system, being pursued at Carleton University, which is used to extract LXe and Ba ions from the TPC, as well as the positioning system required to move the capillary to the site of the $0\nu\beta\beta$ event. The second part involves a setup to extract and identify the Ba ion from GXe delivered by the capillary. For simplicity, this setup will hereafter be referred to as the ‘Ba-tagging setup’. Figure 5.1 shows a photo of the entire Ba-tagging setup (as of November 2025) with the main subsystems labeled starting with the RF funnel on the far left extending to the right with the MRTOF-MS at the end. Figure 5.2 shows an engineering rendering of the Ba-tagging setup consisting of the RF funnel, the LPT

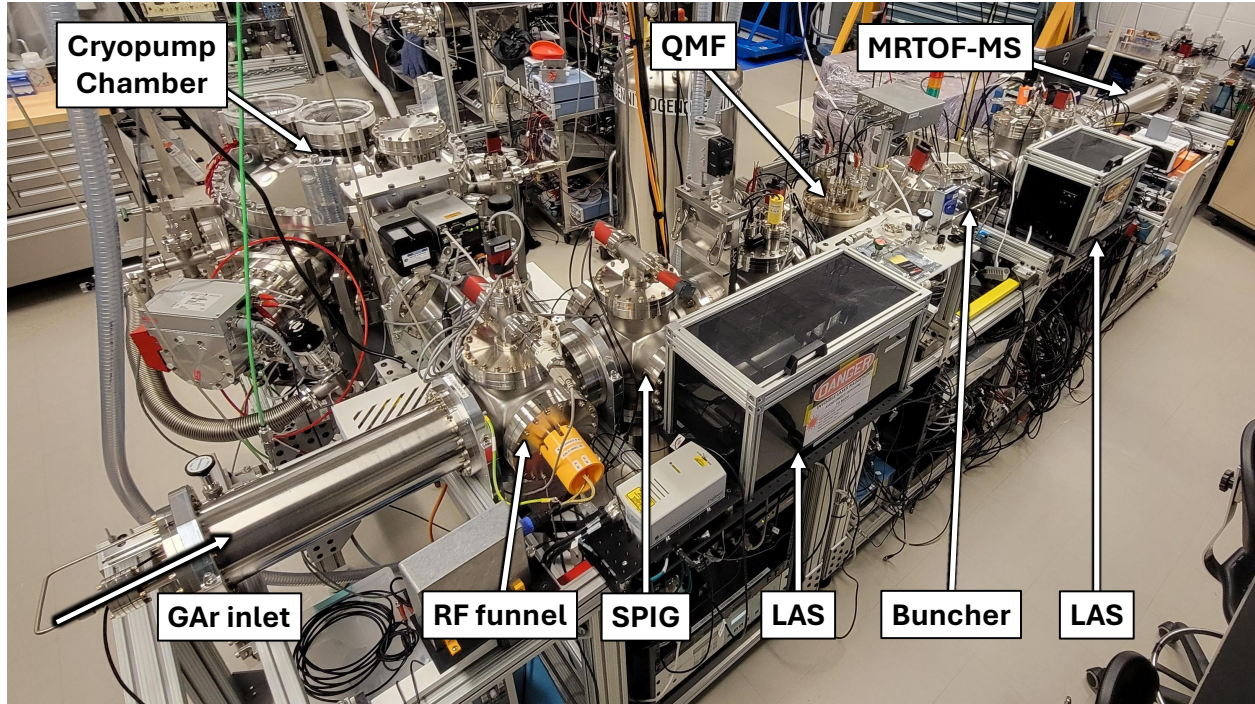


Figure 5.1: Photograph of the Ba-tagging setup with key components annotated, including the RF funnel, the SPIG, the QMF, the ion buncher and the MRTOF-MS. Also highlighted is the cryopump chamber adjacent to the RF funnel which will be used to recover GXe. Two LAS in optical dark boxes are identified, one located upstream from the QMF and the other between the buncher and the MRTOF-MS.

and the MRTOF-MS that are being developed in this work to study ion extraction from GXe. Key sections have been enlarged for emphasis: (1) the RF funnel used for separating Ba ions from GXe; (2) the quadrupole bender assembly with modified Einzel lenses for focusing and steering ions; (3) the ion buncher that is used for trapping and bunching of ions for mass measurements; (4) electrostatic lenses and steerers to direct ions into the MRTOF-MS; (5) one of the two electrostatic mirrors of the MRTOF-MS.

The Ba-tagging setup is installed in 8" ConFlat (CF) ultra-high vacuum (UHV) crosses

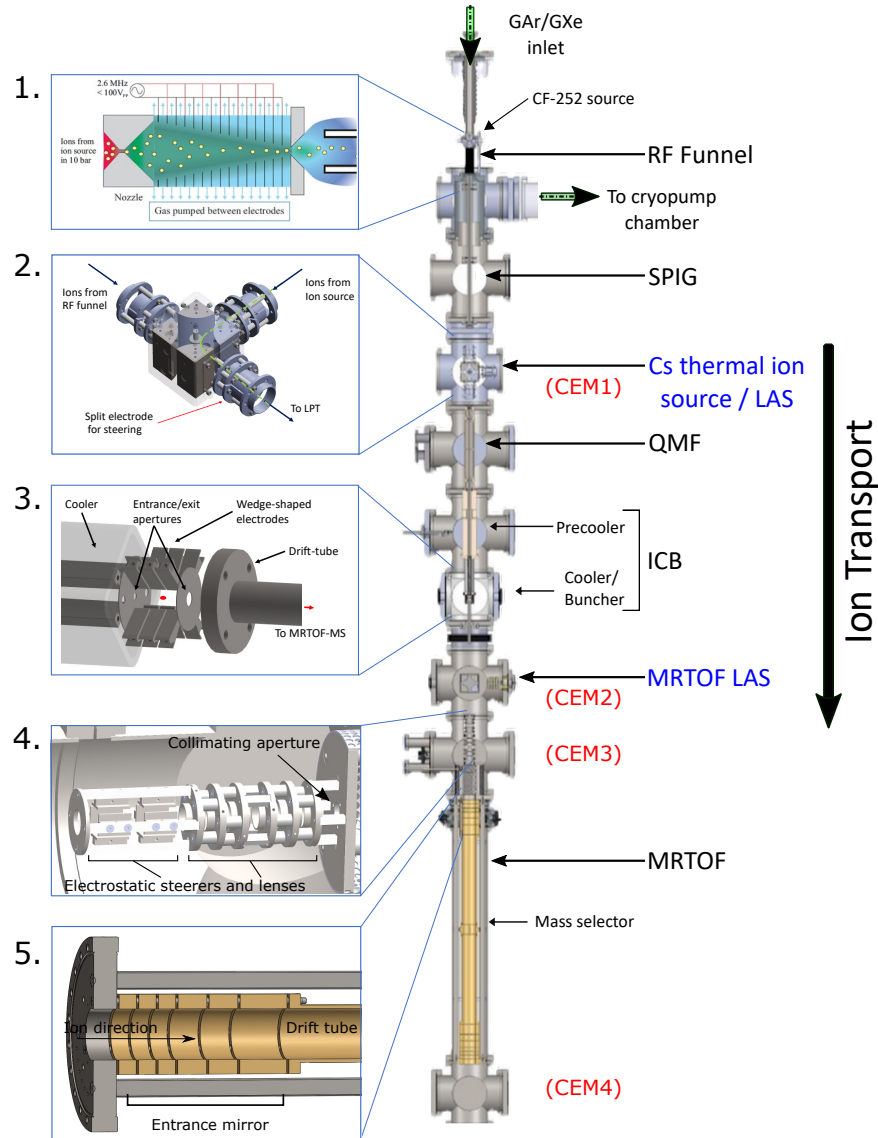


Figure 5.2: Sectioned view of an engineering rendering of the Ba-tagging setup for ion extraction from GXe. Highlighted are key components that enable the high efficiency extraction and transport of ions: (1) RF funnel, (2) quadrupole bender assembly, (3) ion cooler and buncher, (4) electrostatic lenses and steerers, (5) electrostatic mirror electrode assembly of the MRTOF-MS.

and nipples, mounted on a rail-system to facilitate their assembly and disassembly. Each cross is fitted with a Pfeiffer Vacuum HiPace 700 turbo molecular vacuum pump with two exceptions: i) the RF funnel cross is connected to the adjacent chamber fitted with a cryopump for Xe recovery, and ii) the cross housing the SPIG which uses an Edwards STP-A803C Turbo Pump as the HiPace 700 pumps are more suitable for use with gases of atomic/molecular masses less than 80 u [147]. ISEG EHS and EBS high-voltage modules are used to supply DC potentials for all electrostatic components of the setup. A digital waveform generator¹ supplies the sinusoidal signal used to drive the RF funnel, the SPIG, the QMF, and the ion cooler and buncher (ICB). To effectively test and optimize the Ba-tagging setup, various ion sources were installed to deliver ions to the subsystems. These will be discussed in detail in Section 5.1. Highlighted in red in Figure 5.2 are the locations of ion detectors (CEM1–4) that are discussed in Section 5.2 and referenced in later chapters in the context of ion bunching and TOF measurements. A detailed discussion of the vacuum systems, subsystem designs, electronics along with results from their commissioning studies will follow in Chapters 6 and 7.

5.1 Ion Sources

During the commissioning of the Ba-tagging setup, different ion sources were used to test each subsystem independently before tandem operation. The three principal ion sources

¹T344 Highland Technology.

used were: aluminosilicate thermal ion source; laser ablation ion source (LAS); ^{252}Cf driven in-gas ion source.

5.1.1 Aluminosilicate Thermal Ion Source

Aluminosilicate ion sources use emitter materials (e.g. Spodumene) coated onto tungsten which, when heated, produces ions through thermionic emission [148]. In the Ba-tagging setup, the source² is used to supply a $\sim 0.5\text{ nA}$ beam of $^{133}\text{Cs}^+$ ions (the only stable isotope of Cs) when supplied with a heating current of 2.3 A. Figure 5.3 shows the ion source and the electrode assembly used for mounting the source and focusing the ion beam. Also included is an image of the source taken through a window during operation, where the surface exhibits a faint red glow. The energy of the produced ions is controlled by biasing the source mount to the desired voltage. The initial energy of ions is not accurately known but is determined to be $< 1\text{ eV}$, which is close to the ion energy measurements of other aluminosilicate sources [149]. Figure 5.4 presents the measured source output as a function of time. The source's ion current is controlled through the supplied heating current and the applied DC bias on the extraction lenses. Typically, the source requires up to six hours to reach a stable output. This stabilization time is reduced down to around two hours by starting at a higher heating current and gradually lowering it to reach the desired output level once stability is achieved. This source is installed upstream of the LPT and provides a stable ion beam with a mass

²Model 101141, HeatWave labs.

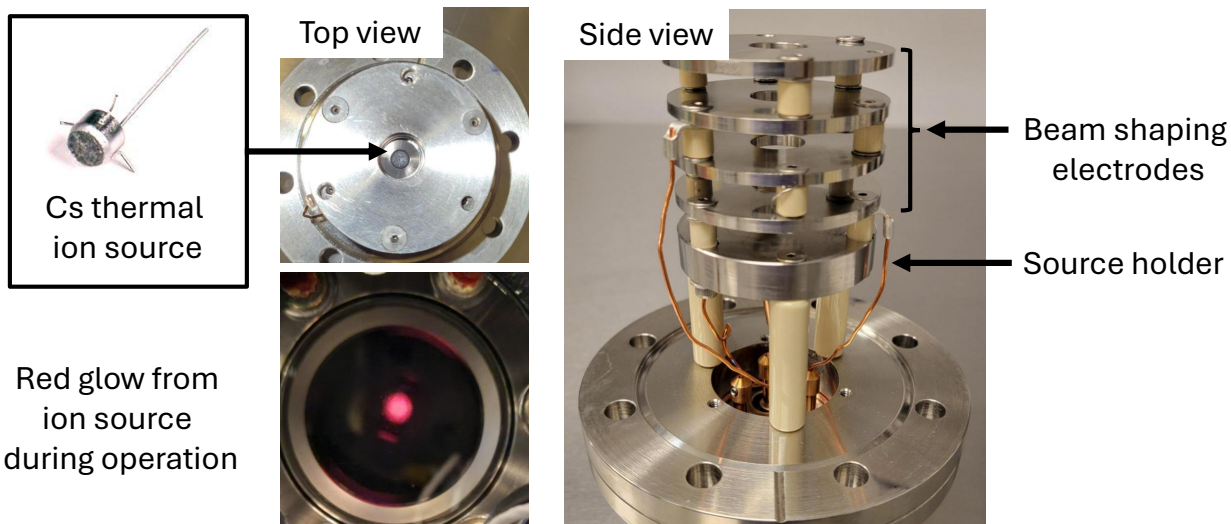


Figure 5.3: Thermal ion source and electrode assembly used for mounting the ion source and focusing of the ion beam. The left panel shows the ion source, visible at the center of the top-view image. Also shown is a photograph of the source taken through a glass window during operation, where the emitting surface exhibits a faint red glow.

close to that of ^{136}Ba . Sources like the Cs aluminosilicate source are useful due to their stable output over long periods but are limited to the availability of emitter materials.

5.1.2 Laser Ablation Ion Source

A laser ablation ion source (LAS) uses focused laser pulses to vaporize a target surface, ejecting material from its surface and producing ions [151, 152]. In contrast to aluminosilicate sources, a LAS is more versatile and can be operated with a larger variety of target materials [153]. The LAS has been studied in the past as an alternate ion source for Ba-tagging and was used to perform TOF measurements with the MRTOF-MS during

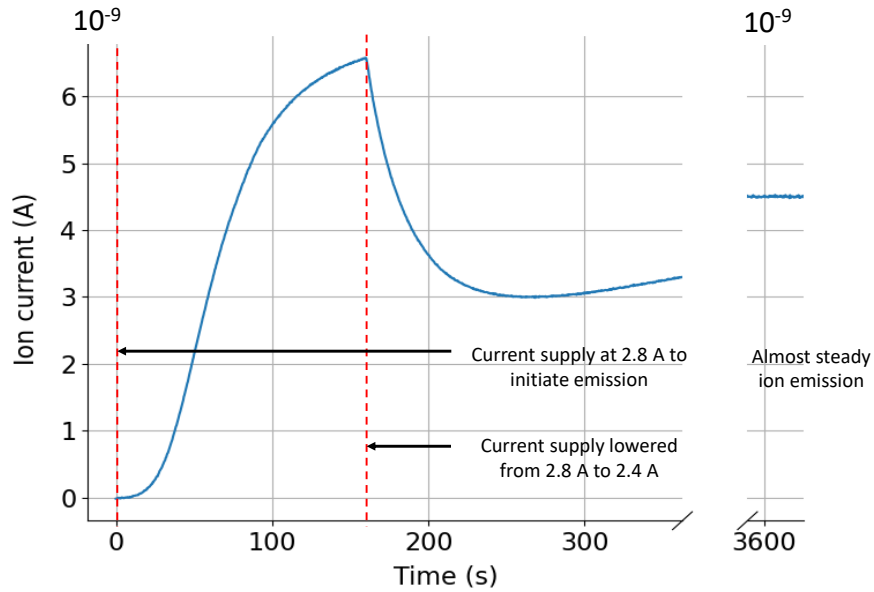


Figure 5.4: Output of the Cs ion source as a function of time. To reduce the time for the ion current to stabilize, the source is initially operated at a high heating current, here 2.8 A, to initiate ion emission and later reduced to reach the target ion current output. Figure reproduced from [150].

its commissioning [125, 154, 155]. Figure 5.5 shows the LAS that was built to replace the aluminosilicate thermal ion source. A 349 nm UV laser³ is directed into the vacuum chamber via a $\varnothing 1.4''$ fused silica viewport and is focused onto the target using a plano convex lens ($f = 500$ mm). Since laser ablation is destructive in nature, ion production rapidly decreases during repeated ablation at the same location. Thus, the position of the laser spot on the target is moved and controlled using linear actuators⁴ to move the last mirror outside the vacuum chamber, allowing for the uniform ablation of the target surface.

³Spectra-Physics Explorer One

⁴Physik Instrumente (PI) Actuator: N-472.210 PiezoMike Linear Actuator, Controller: E-871.1A1N Digital Controller.

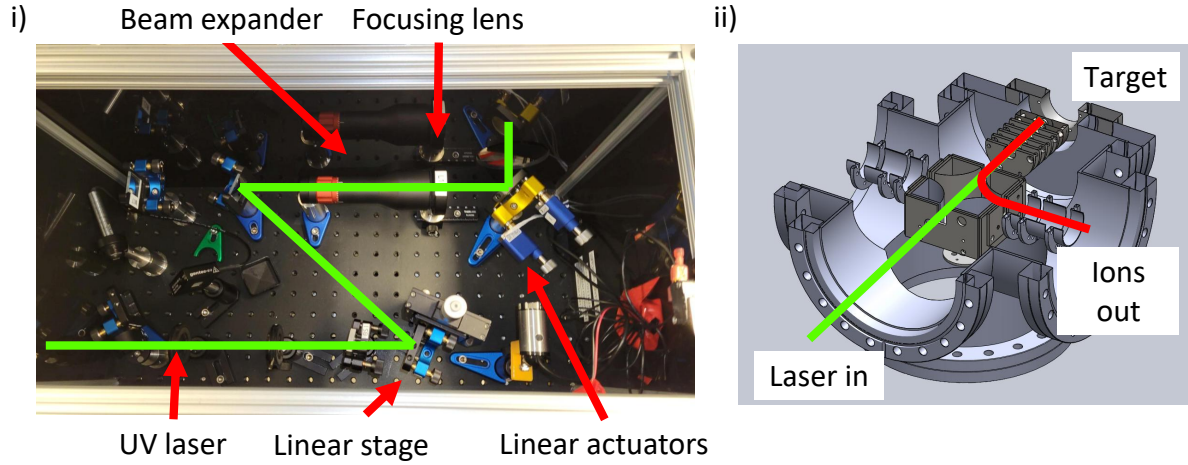


Figure 5.5: Laser ablation ion source dark box and bender assembly CAD model rendering. (i) A pair of mirrors is used to adjust the laser height and inclination before going through a beam expander and focusing lens. The focused beam is then directed into the vacuum chamber using an actuated mirror. (ii) The laser enters the vacuum chamber through a fused silica viewport and passes through the quadrupole bender to reach the target. Ions produced are then supplied to the LPT by the quadrupole bender.

As previously mentioned, the LAS can provide a wide range of ion species. Figure 5.6 shows a target that was machined using oxygen-free high thermal conductivity (OFHC) copper and an assortment of material rods. The main purpose behind this target was to test laser ablation of a variety of materials to supply to the LPT and the MRTOF-MS subsystems, and characterize them over a large ion mass range. The target was prepared by machining 9 evenly spaced wells in a 12.7 mm (0.5") thick OFHC copper disk (refer to Figure A.1 for exact dimensions). Rods of various materials were cut to the depth of the wells using a diamond saw and were inserted into the copper disk. A hydraulic press was

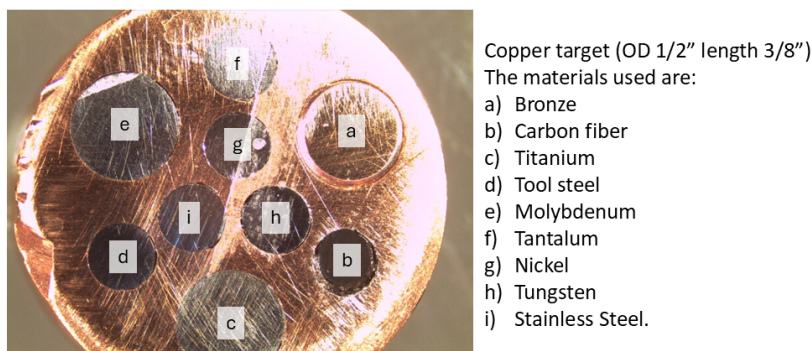


Figure 5.6: Multi-element LAS target. The target was machined from OFHC copper and fitted with nine different material rods to enable ablation of multiple elements without target changes.

used for 8 of the 9 materials to ensure that the rods were fixed in place. For the carbon fiber component, indium was used as a filler to ensure a proper fit, as its malleability allows it to conform to surface irregularities, and indium's low vapor pressure makes it suitable for UHV applications. The target surface was then sanded to achieve a flat and smooth finish, which is necessary for uniform laser ablation. The target was then installed in place of the Cs ion source to test laser ablation.

Figure 5.7 shows an ion current heatmap generated by moving the laser spot and ablating the target over a rasterized grid. Ion current was measured at each position to map the spatial variation in ion yield. The ion production through LAS is highly dependent on the ablation threshold of the material being ablated [156]. This dependence is evident in the resulting heatmap, which shows distinct contours corresponding to discrete changes in ion current across different materials. The heatmap image of the target surface was then used to locate

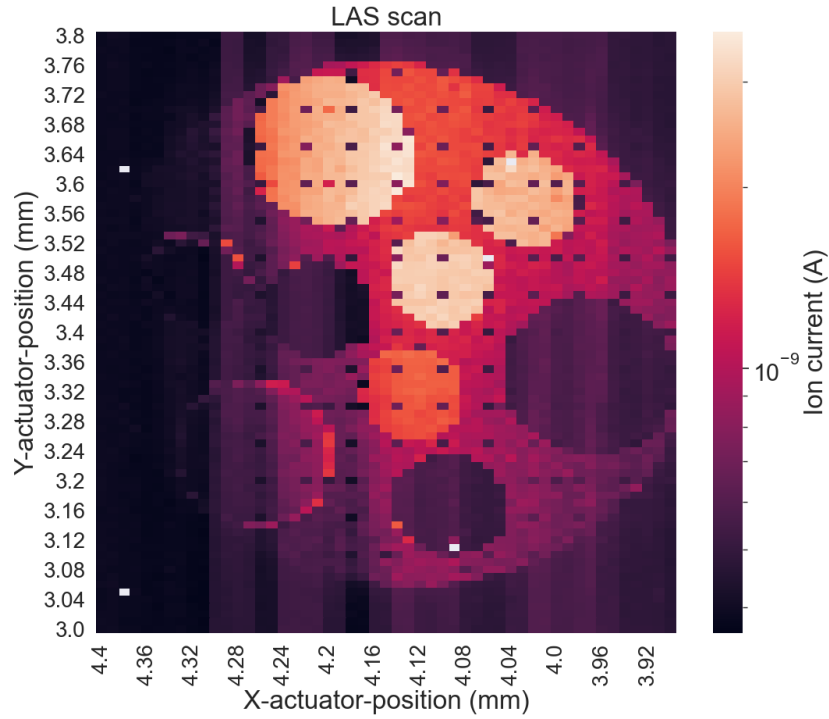


Figure 5.7: Heatmap of the measured ion current produced by the laser ablation of the multi-element target. The laser position on the target is scanned over a rasterized grid using a mirror mount driven by a linear actuator. For each laser spot on target position, the ion current is measured and averaged over 5 s. The sharp change in the averaged ion current at the edges of material rods arises from differences in ablation threshold for respective materials.

the positions of various materials and to calibrate the motion of the linear actuators. This target will be used in the future to perform mass calibrations of the MRTOF-MS and test the resolving powers of both the QMF and MRTOF-MS for different ion mass ranges.

5.1.3 In-Gas Ion Sources

For ion production in-gas, a ^{252}Cf source⁵ is installed upstream from the RF funnel. ^{252}Cf has a half-life of 2.6 years and decays via α decay (96.9%) and spontaneous fission (3.1%) [157, 158]. The fission fragments have masses distributed around 106 u and 142 u [159], with a small fraction of the heavier fragments being Ba that can be used to tune and test the system. Ions produced by spontaneous fission are then carried by a carrier gas (GAr/GXe) to the RF funnel.

One shortcoming of this type of source is that ^{136}Ba constitutes only a small fraction of the fragmentation products, where the process itself only has a low branching ratio. The main α -decay mode is expected to produce large amounts of carrier gas ion in addition to the fission fragments. To address this limitation, an alternative source is being studied to selectively produce Ba ions in a high pressure environment using laser ablation [154]. While conceptually similar to the previously described LAS, this approach operates in a gas environment rather than in vacuum. The source is currently being studied to investigate ion properties such as ion angular distribution, energy, and charge state as a function of different gas pressures, laser power and extraction potentials. The future goal would be to use this source in place of the Cf source to produce only Ba ions.

As this discussion of ion sources has shown, considerable effort has been devoted to generating ions in different environments by using different techniques and materials.

⁵Activity measured in 2018 - 3.3 kBq, model AF-252-A2, Eckert & Ziegler Isotope Products.

However, the successful utilization of these ions ultimately depends on the ability to measure and characterize them with high precision and efficiency. This makes the instrumentation used for their detection just as important.

5.2 Ion Detection Instrumentation

The main figures of merit used in the tuning of the Ba-tagging setup are ion currents, ion count rates, and ion TOF spread. During the commissioning of the LPT, the ion transport efficiency between successive stages was optimized using a 1 nA ion beam from the Cs ion source. Ion current was measured at various locations by collecting the ion beam onto a negatively biased electrode with a digital multimeter⁶. This approach was useful down to ion beam currents as low as 50 pA. Beyond this threshold, noise fluctuations dominated the current measurements, limiting its usefulness in regions with very poor transport efficiency prior to tuning, as well as in bunched ion applications where the overall ion count is low.

For operations involving low ion count rates or measurement of the TOF of ions, channel electron multipliers (CEMs) are used. Charged particles are accelerated toward the CEM surface, where they produce secondary electrons upon impact. The emitted secondary electrons subsequently travel deeper into the CEM tube and accelerate under a potential (~ 2 kV), striking the surface and in the process producing more secondary electrons. Through a cascade of secondary electron emissions, the incident charge is

⁶DMM 34465A Keysight Technologies

amplified by a factor of over 10^7 [160–162]. There are a total of four CEM devices (labeled as CEM1-4) installed in the Ba-tagging setup with their locations indicated in Figure 5.2. Two methods are used to detect ions with CEMs: ions are either deflected toward the CEM using a push electrode, or the CEM is inserted into the ion path using linear actuators⁷. Figure 5.8 shows the mounting configuration of the CEM devices in the Ba-tagging setup. For the actuator-mounted CEM2 and CEM3, holders were 3D printed using Formlabs Durable Resin (V2) to electrically isolate the devices. The printed parts initially present some low-level outgassing, likely due to absorbed water between the baking process and installation. The vacuum in their respective locations eventually reached the original levels several days after installation. Similar results have been seen with studies done using Formlabs Clear Resin that demonstrated SLA printing as a good option for rapid prototyping of parts for high-vacuum systems [163].

With the characteristics and functioning of the ion sources and detectors now discussed, the focus will shift to the subsystems that constitute the Ba-tagging setup. These subsystems have been previously studied as part of the prototyping process and used to demonstrate the performance for the Ba-tagging application. Previous works include:

- The RF funnel was previously studied in detail to demonstrate ion extraction from gas using various radioactive ion sources [121, 124].
- The LPT was simulated and optimized through various iterations of prototyping before

⁷HTL-275-2, 2" linear motion feedthrough with DC stepper motor, Accu-Glass Products, Inc.

the final design was fabricated [116].

- The MRTOF-MS was designed and commissioned using a LAS and demonstrated a resolving power of 20 000 [125].

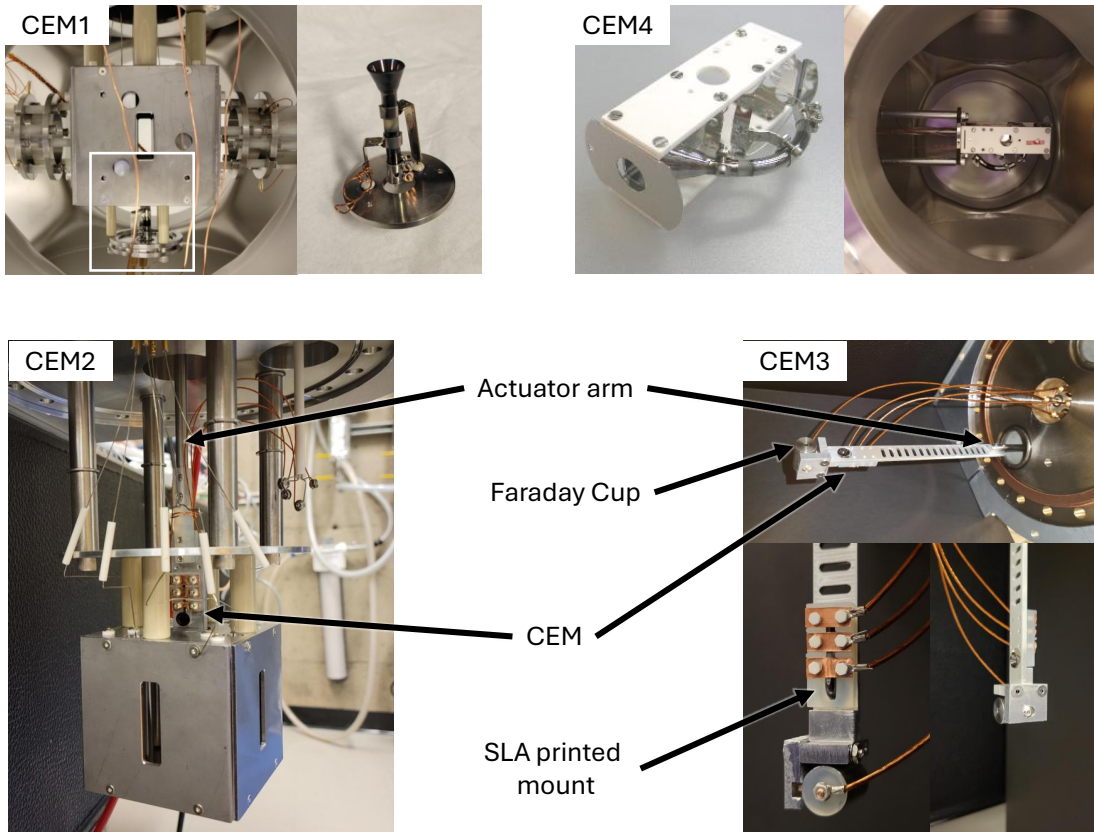


Figure 5.8: CEM devices used in the Ba-tagging setup. (Top) CEM1 and CEM4 are positioned at the exits of the RF funnel and MRTOF-MS, respectively. CEM1 is mounted inside a quadrupole bender located between the LPT and RF funnel subsystems. (Bottom) CEM2 and CEM3 are mounted on actuators, allowing flexible positioning between the LPT and MRTOF-MS. CEM2 is inserted into the quadrupole bender located between the LPT and MRTOF-MS subsystems.

Building on the past work where devices were characterized individually, the subsequent chapters describe the commissioning of these subsystems in their current configuration as an integrated beamline, along with measurements and key results obtained over the course of their testing and tuning. More specifically, Chapter 6 presents the design of the RF funnel subsystem, along with its associated electronics, and discusses results from measurements performed using GAr, while Chapter 7 describes the LPT subsystem, including results from commissioning studies and TOF measurements of bunched ions using the MRTOF-MS.

Chapter 6

RF Funnel: Design and Ion Extraction Characterization

RF funnels are widely used in ion manipulation systems to efficiently capture and guide ions from regions of relatively higher pressure into lower-pressure environments while minimizing losses [138]. In the Ba-tagging setup, the RF funnel is responsible for receiving the GXe containing the Ba ion from the capillary and extracting the ion into a high-vacuum environment.

This chapter presents the RF funnel subsystem. Section 6.1 describes the subsystem design, vacuum system, associated electronics, and operating principles, while Section 6.2 presents the data acquired during recommissioning, focusing on the characterization of ion transport and overall system performance under various operating conditions.

6.1 RF Funnel and SPIG Assembly

The RF funnel consists of 301 annular-disc-shaped electrodes of 0.1 mm thickness with inner diameter decreasing from 16 mm at the entrance to 1 mm at the exit [122]. The separation of the Ba ion from GXe takes place inside the RF funnel, where the accompanying gas is pumped out through the 0.25 mm wide gaps in between the stacked electrodes while RF potentials repel the ion. A more accurate term for the design used here is RF-only funnel. Unlike the designs that apply an axial DC potential gradient to move the ions from the entrance to the exit of the RF funnel, this design uses the residual carrier gas flow to propel the ions [138]. This approach eliminates potential sources of contaminants associated with electrical components such as resistors typically used in creating such an axial DC field. Therefore, the residual gas flow carries the ions across, while the RF field and conical geometry of the RF funnel focuses the ion toward the axis for efficient transmission.

A converging-diverging supersonic-nozzle, positioned upstream of the RF funnel, is used to expand the high-pressure GXe at the inlet into a supersonic jet, ideally producing nearly parallel gas streamlines and a reduction in pressure [121]. For the purpose of commissioning the RF funnel, GAr was used as carrier gas to supply ions from the ^{252}Cf source to the RF funnel. GAr was used due to its lower cost than GXe. During GAr operation, the gas is exhausted to the building exhaust, whereas subsequent operation with GXe will involve gas recovery via cryopumping. The GAr injected from the gas inlet carries ions produced by the

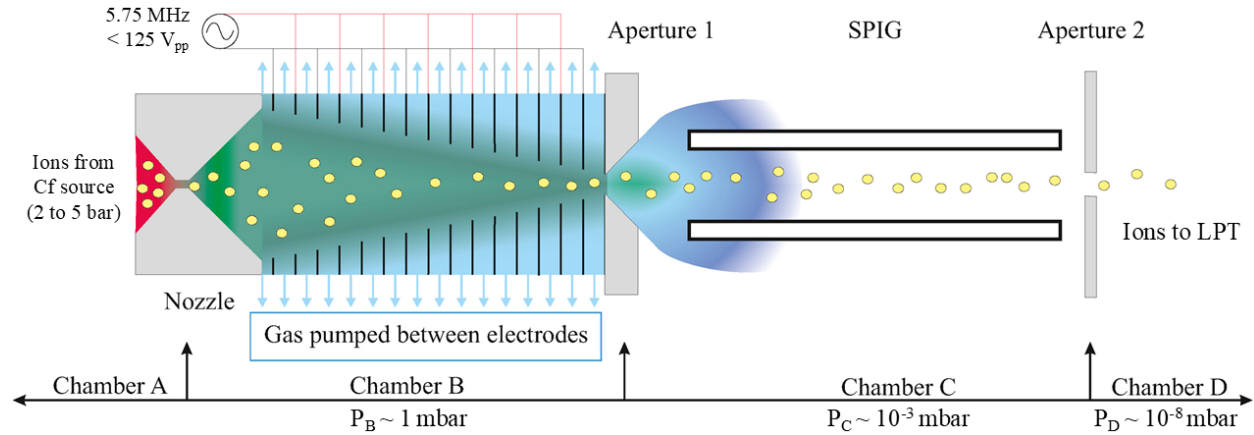


Figure 6.1: Schematic diagram of the RF funnel subsystem. Ions produced by the ^{252}Cf source (Chamber A) pass through a supersonic nozzle with GXe (or GAr). (Chamber B) The ions propagate forward under the influence of the residual gas flow, while the RF field prevents losses by repelling them away from the electrodes. The majority of the gas escapes from between the inter-electrode spacing. (Chamber C) Ions are transported through a differential pumping stage by a SPIG, ultimately reaching (Chamber D) a high-vacuum environment. Figure reproduced from [121].

^{252}Cf source through the supersonic nozzle, as shown in Figure 6.1.

Ions extracted from the RF funnel through a $\varnothing 1 \text{ mm}$ aperture (Aperture 1 in Figure 6.1) pass through a 480.5 mm long SPIG to allow for differential pumping between the RF funnel chamber, typically operated at 1 mbar, and the downstream section, which operates at pressures below 10^{-7} mbar . The flow of gas into and out of the SPIG chamber is regulated by flow-limiting apertures ($\varnothing 1 \text{ mm}$). Figure 6.2 shows pictures of the RF funnel, the SPIG, and the cryopump chamber, connected through a proportional gate valve (PGV).

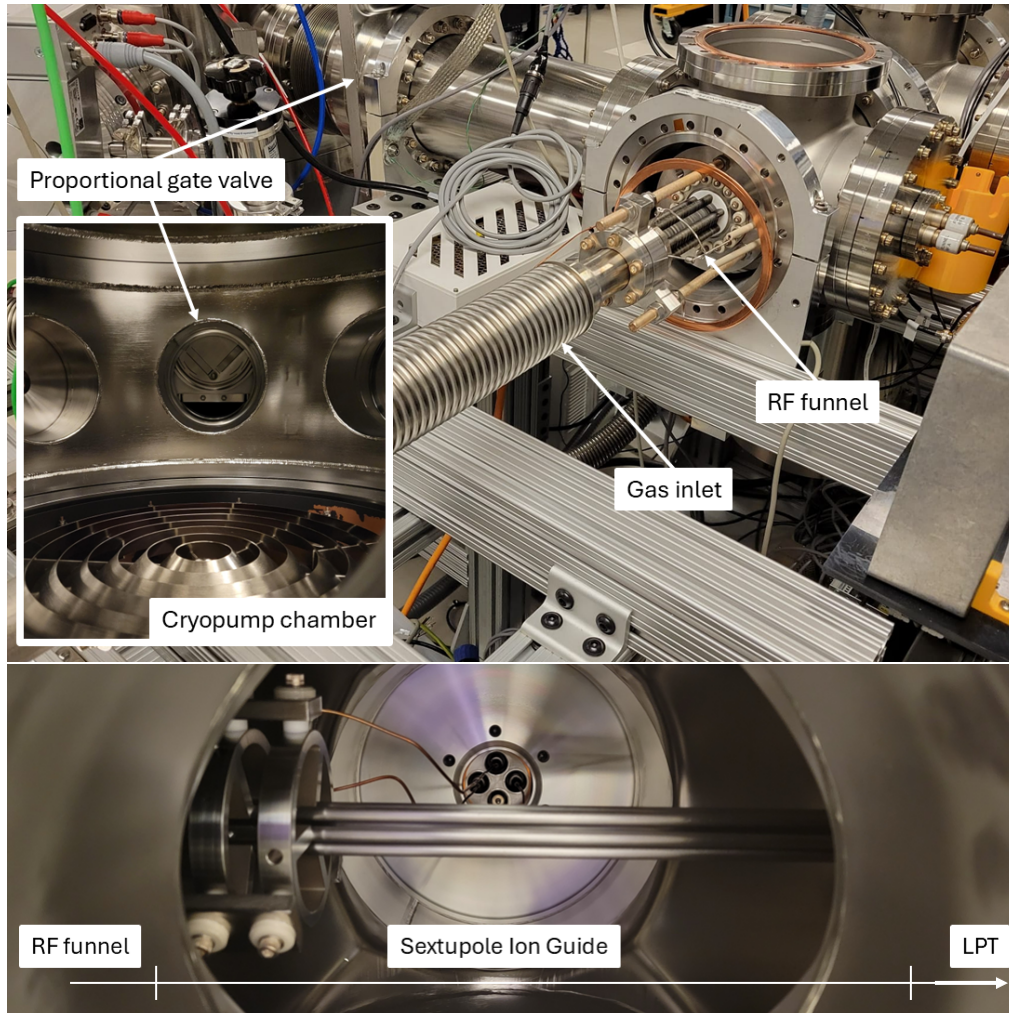


Figure 6.2: Pictures of the RF funnel subsystem. (Top) The gas inlet and bellows connecting to the RF funnel. (Bottom) The SPIG and its electrode mounts, which also serve to supply the RF signal. (Insert) Picture of the cryopump chamber.

6.1.1 Vacuum Layout and Differential Pumping

The current layout of the vacuum system improves on challenges observed in the previous studies [121, 124]. The original vacuum system of the RF funnel was housed inside a large

¹Marathon CP-20 Cryopump, Sumitomo

cryopump chamber through a PGV² (GV003). The valve position of the PGV provides control over the RF funnel chamber pressure by regulating gas flow to the cryopump chamber. Without any gas flow, the SPIG chamber pressure reaches $< 10^{-8}$ mbar after one day of pumping. Similarly, the ultimate pressures in the RF funnel chamber with GV003 open and turbopump (TMP007) running reaches 5×10^{-8} mbar.

The system currently has a pressure relief valve and a burst disc installed on the funnel chamber and cryopump chamber respectively to prevent overpressurizing the system during commissioning using GAr. Additionally, a software failsafe has been implemented to automatically open the PGV in the event of excessive pressure buildup within the RF funnel chamber. In the future, for operating with GXe, the pressure relief valve on the RF funnel chamber will be replaced with an in-line burst-disc that exhaust directly into the cryopump chamber, which in turn will be coupled to a gas handling system responsible for supplying GXe, thereby preventing Xe loss. This gas handling system currently holds approximately 5 kg of Xe. For a flow rate of up to 0.3 g/s, the gas handling system can theoretically operate for over 4 h per run before the need for recovery [124].

6.1.2 RF and DC Electronics

The RF funnel and the SPIG are driven by two out-of-phase RF sinusoidal potentials operating at the respective resonance frequencies for maximum power transfer. RF power

²64244-UEHY, VAT Valve

amplifiers are used to reach the desired amplitudes for operation. The amplified signal is supplied to an RF circuit similar to the one shown in Figure 6.4. The resonance frequency of the RF system is typically set to the desired operating frequency of the system by using a combination of transformer turn ratios between the primary and secondary (M:N) and series capacitors (C1, C2). The current circuit for the RF funnel and SPIG are turned to operate at 5.75 MHz and 2.3 MHz, respectively. Additionally, a bias potential (VDC) is applied to the electrodes through the center tap of the secondary as shown in Figure 6.4. In contrast to the SPIG RF circuit, which utilizes a ferrite core, the RF funnel circuit incorporates an air core to prevent excessive heating that was observed in ferrite cores at the high power levels required for RF funnel operation. High-power feedthroughs and nickle-plated OFHC copper ($\varnothing 0.064''$) wires for in-vacuum connections are used to enable operation at high amplitudes without overheating.

6.1.3 RF Funnel Operation

The recommissioning of the RF funnel subsystem following assembly in its upgraded vacuum system was performed using GAr as a cost-effective substitute for GXe. While operating with GAr, roughing vacuum is maintained in the cryopump chamber with a scroll pump³ (EDP001). The bulk of the GAr in the RF funnel chamber is evacuated through the PGV (GV003) and a fraction which flows through the SPIG is pumped by a turbopump (MLP001)

³XDS35i Dry Scroll Pump, Edwards Vacuum.

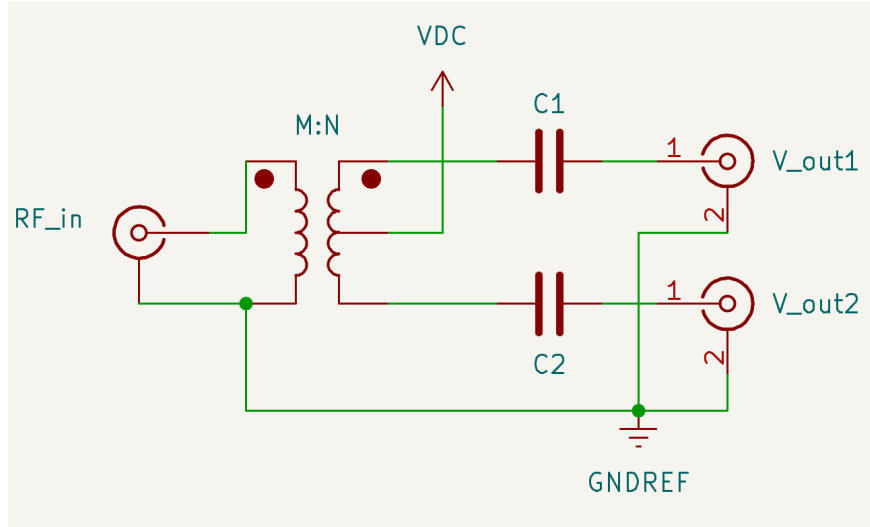


Figure 6.4: Example RF circuit diagram used to drive the RF funnel and the SPIG. Figure A.3 shows pictures of the circuitry in metal enclosures that are used for the RF funnel and SPIG.

backed by a root pump⁴ (ACP003). During operation with GXe, the gas pumped out from MLP001 will be collected in the cryopump chamber via the all-metal valve (AMV002) to recover most of the Xe going into the SPIG chamber. Only a small fraction of the GXe flowing downstream from the SPIG chamber is lost.

Ions flow from the RF funnel to the SPIG once gas flow is initiated. A forward potential gradient is applied by biasing the entrance aperture (10 V), the SPIG (9 V), and the exit aperture (0 V) to direct ion motion towards the QMF. Ions are detected using CEM1 located at the base of the LPT quadrupole bender, shown in Figure 5.8. A push electrode located on the face opposite to the CEM is used to deflect and detect incoming ions. SIMION 8.1 was used to simulate ion transport from the SPIG and optimize the potentials for the

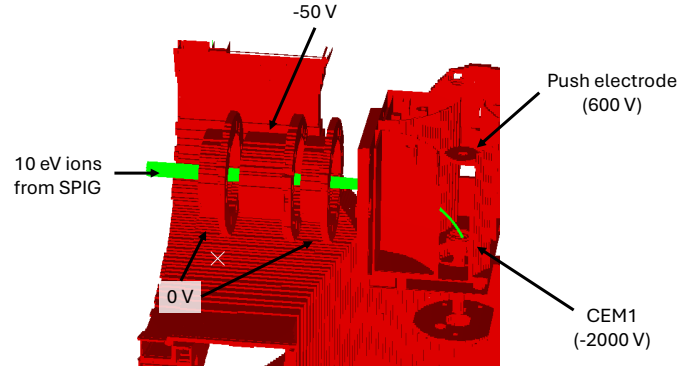
⁴ACP 28, Multi-stage root pump, Pfeiffer Vacuum.

Einzel lens and push electrode, shown in Figure 6.5a, to maximize ion collection. Using the optimized voltage values, the ion count rate was measured at CEM1 and used as a diagnostic to characterize the RF funnel subsystem's response and to adjust the applied DC biases under varying GAR flow conditions. The corresponding results from these preliminary GAR studies are discussed later in this Chapter. Finally, the same simulation was used to initially optimize ion transport from the SPIG to the LPT, as illustrated in Figure 6.5b. In this configuration, all electrodes except the Einzel lenses were maintained at ground potential. The LPT was tuned to enable efficient ion transfer at approximately 10 eV from the RF funnel subsystem to CEM2, which is positioned downstream of the ion buncher. The results of this simulation will be used to establish an initial reference measurement, serving as a baseline for subsequent optimization.

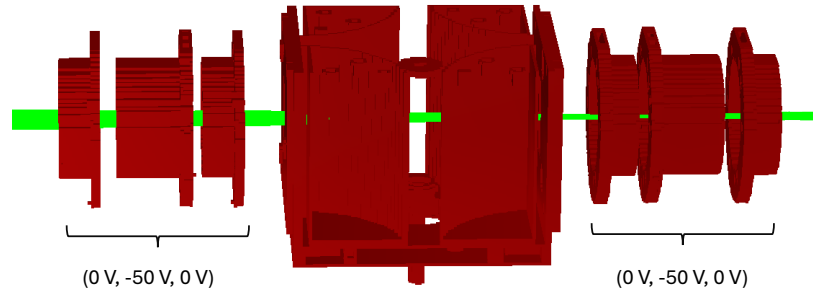
With the operation and design considerations of the RF funnel subsystem established, the next step in the commissioning process was to characterize the performance of the system. This was accomplished using Ar as the carrier gas for the ions from the ^{252}Cf source.

6.2 RF Funnel Recommissioning

The RF funnel presented in this chapter was recommissioned following its previous operation at Stanford University, where ion extraction from GAR, gaseous krypton (GKr), and GXe was studied using a ^{252}Cf source [121, 124]. The tests shown here were conducted using GAR to benchmark the current ion transmission rates, and determine safe operation ranges for



(a) Ion detection on CEM1. Push electrode and lens potentials are varied to maximize ion collection with the CEM. Bias potential for CEM is defined by the manufacturer as -2 kV. Ion trajectories are shown in green.



(b) Ion transport simulations for optimizing Einzel lens potentials. The configuration shown here provides the least spacial spread going into the QMF. Ion trajectories are shown in green.

Figure 6.5: SIMION simulation of the LPT quadrupole bender with ions originating from the SPIG. Ions with an initial energy of 10 eV and a circular position distribution of 2 mm radius were propagated toward the LPT. Ion focusing and collection were optimized by simultaneously varying the voltages of the Einzel lens and push electrodes. The voltage settings that yielded the minimum spatial spread at CEM1 and the LPT entrance are shown.

the electronics and the vacuum system.

6.2.1 Pressure Control System

The gas pressure in the chamber housing the RF funnel (P_{chamber}) is a key parameter governing its operation and a key driver of ion transport. The current vacuum system features a PGV to regulate gas pressure inside the RF funnel chamber. This is a key improvement over previous setups where the cryopumping rate, and in turn the funnel chamber pressure (P_{chamber}), could not be precisely controlled [121]. The position of the PGV is defined relative to its full vertical travel, where 0 corresponds to a fully closed gate valve and 100 to a fully open position. Intermediate positions are also allowed, with a minimum step size of 0.001. To characterize the system response to varying inlet pressures, P_{chamber} was measured as a function of GAr inlet pressure, with the PGV position fixed at 3, as shown in Figure 6.6. P_{chamber} was found to be linearly dependent on the inlet pressure such that $P_{\text{funnel}}(t) = a P_{\text{inlet}}(t - b) + c$, where $a = 1.02 \times 10^{-3}$ is a scaling factor, $b = 14.46 \text{ s}$ represents the delay between a change in the inlet pressure and its effect on the funnel chamber pressure, and $c = -8.4 \times 10^{-2} \text{ torr}$ is a constant offset.

Figure 6.7 shows the response of P_{chamber} to different PGV positions for a constant inlet pressure of 2600 torr. The minimum valve position for stable operation was found to be 1.5. Beyond this position, P_{chamber} rises rapidly without stabilizing, indicating that the combined gas out-flow through the PGV and the SPIG chamber is insufficient to evacuate the injected

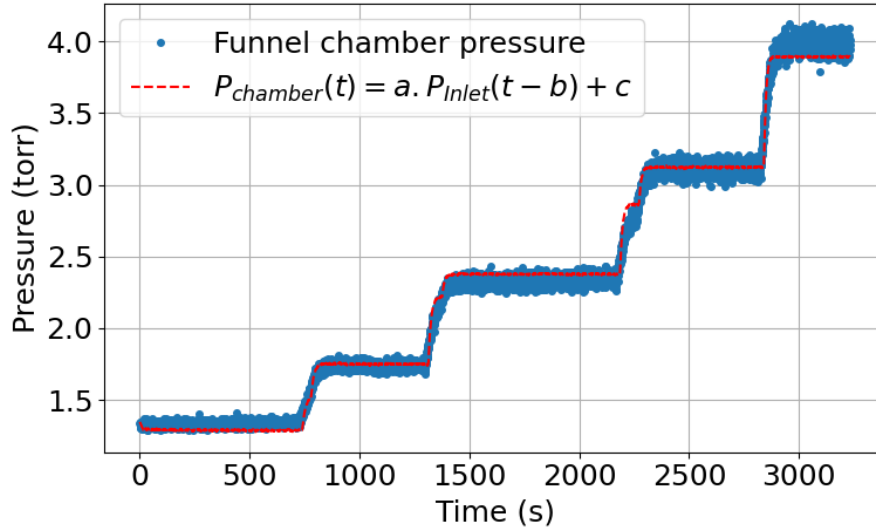


Figure 6.6: Funnel chamber pressure (P_{chamber}) as a function of inlet gas pressure (P_{inlet}) with the PGV set to position 3. The red curve shows the linear fit using P_{inlet} to reproduce P_{chamber} .

gas. Maximum pressure control sensitivity was observed for PGV positions ranging between 1.5–3. Beyond valve position 3, the pressure differential across the PGV goes to zero due to the significantly large conductance resulting in negligible change in P_{chamber} .

These results indicate that the funnel chamber pressure can be controlled with a ~ 15 s response time, enabling maintenance of a stable funnel chamber pressure when operating with GXe. With the funnel chamber pressure shown to be both stable and controllable, the next steps were to evaluate ion transport efficiency through the system and to test the output of the RF circuitry. The following subsection presents details on ion-transmission measurements performed under controlled pressure settings to quantify the performance of

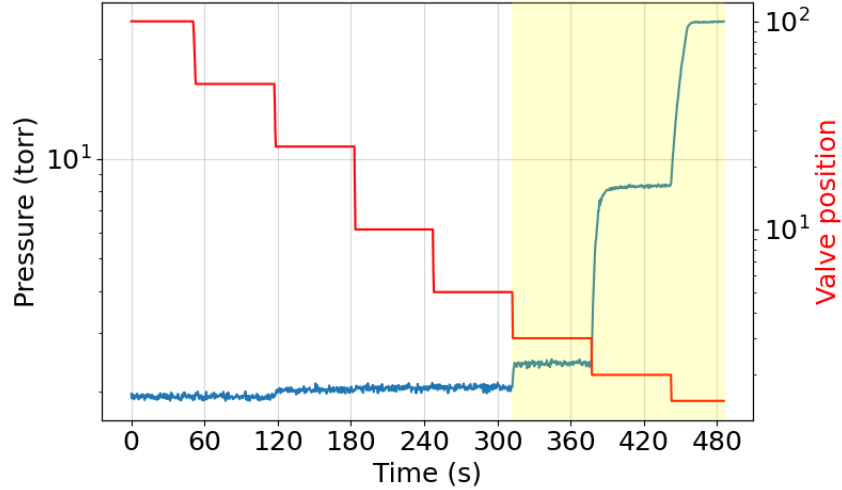


Figure 6.7: Funnel chamber pressure (P_{chamber}) as a function of PGV position for a constant inlet pressure of $P_{\text{inlet}} = 2600$ torr. The most significant control over the funnel chamber pressure occurs within the position range of 1.5–3, highlighted with a yellow accent background. Operation beyond position 1.5 is unfeasible as P_{chamber} continually increases without stabilizing.

the RF funnel in preparation of ion extraction studies using GXe.

6.2.2 Ion Transmission through the RF Funnel

Simulations of the RF funnel have suggested higher ion transport efficiency when operating at higher RF frequencies. Previous measurements were constrained to an operating frequency of 2.6 MHz due to hardware limitations [124]. This study examined ion extraction in GAR as a function of the RF amplitude at an operating frequency of 5.75 MHz. This provided an initial assessment of behavior of the RF funnel under these new conditions and helped determine the limits of RF circuitry to safely deliver the required power for operation.

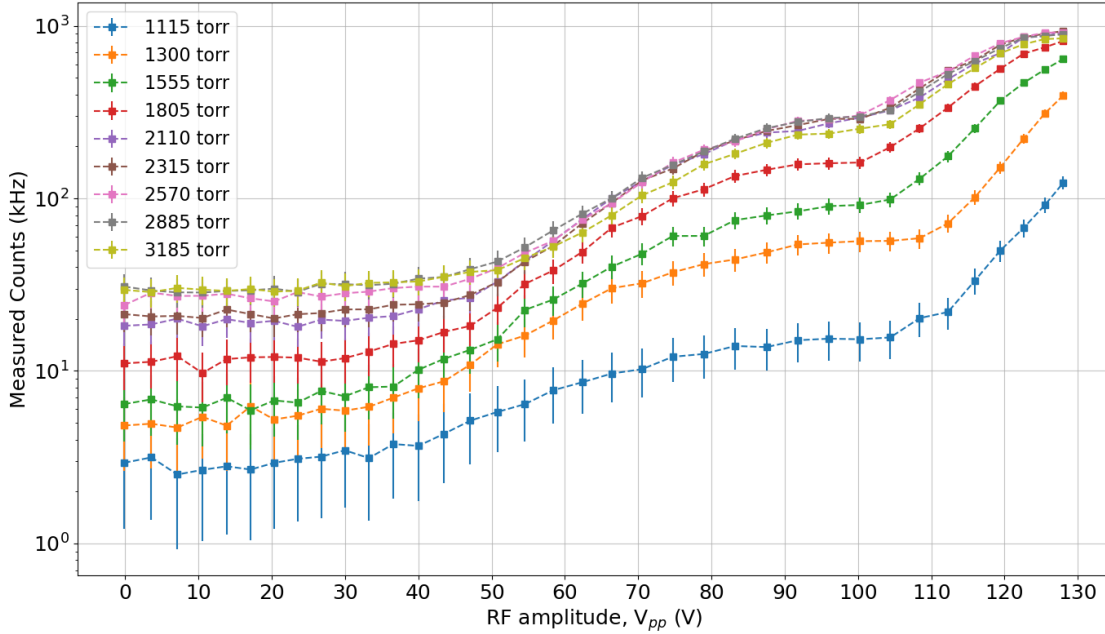


Figure 6.8: Ion transmission in the RF funnel at various inlet pressures as a function of RF amplitude. The observed variation in ion count follows previously observed trends up to $100 V_{pp}$.

Figure 6.8 shows the ion counts measured with CEM1 as a function of RF amplitude for different inlet pressures. The RF amplitude scans show similarity in trends observed in past results for RF amplitudes of up to $100 V_{pp}$ [124]. Here, the majority of the ions detected are expected to be ionized Ar produced by α particles from ^{252}Cf decay and potential molecular contaminants. This is inferred from the activity ($< 0.8 \text{ kBq}$) of the ^{252}Cf source used for this measurement which is much lower than the observed ion count rates that are $> 100 \text{ kHz}$. Beyond $100 V_{pp}$, a second increase in count rate was observed across all gas pressures, which was not previously observed in the GXe data [124]. One possible source of this increase could be the impact ionization of GAr by ions in the RF funnel or an increase in the transmission

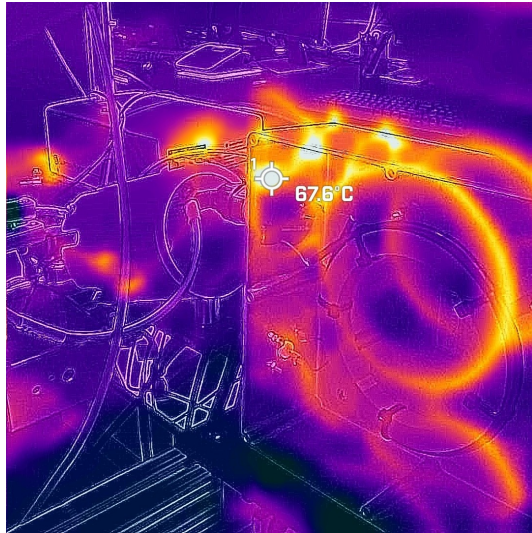
efficiency of a secondary ion species. It was also observed that for pressures above 2000 torr, the ion count rate is mostly independent of the inlet pressures, indicating either $\sim 100\%$ transport efficiency, the saturation of ions produced by α particles, or a combination of the two effects. These possibilities will be explored in more detail in future work through mass-identification studies of the extracted ions using the LPT and MRTOF-MS subsystems.

Stable operation was found to be limited to a maximum amplitude of $125 V_{pp}$. The main limiting factor in the current RF system was found to be the overheating of the series capacitors used at the output of the RF funnel transformer. The 2200 pF high-voltage capacitors used to resonate the system at the frequency of 5.75 MHz are rated to operate at temperatures of up to 80°C . However, it was observed that for RF amplitudes above $125 V_{pp}$ the capacitor temperatures exceed 100°C , leading to failure of the capacitor within a few minutes of operation. Figure 6.9 shows the capacitor temperatures for RF amplitudes of $100 V_{pp}$ and $150 V_{pp}$. Measurements at higher potentials will require replacing the existing capacitors with units rated for higher power applications⁵.

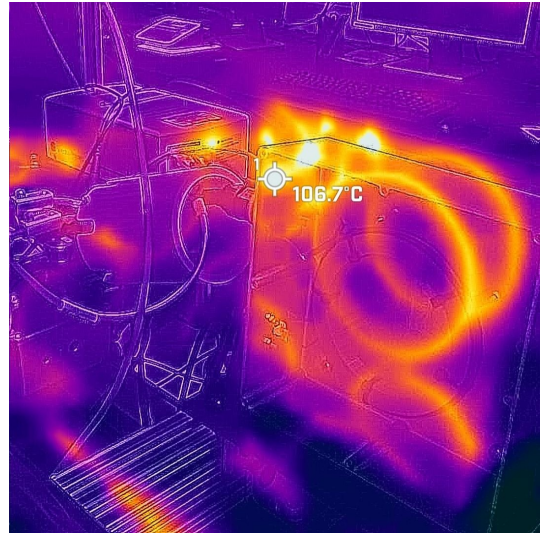
6.2.3 Ion Transmission through the SPIG

Ions from the RF funnel pass through a flow limiting aperture to reach the SPIG. In the SPIG, ions lose their kinetic energy via collisions with the residual gas in the chamber. The energy of the ions exiting the SPIG is thus defined by the SPIG bias potential. The

⁵Potential replacement: **HV Ceramic capacitor**



(a) RF amplitude: $100 V_{pp}$,
capacitor temperature: 67.6°C .



(b) RF amplitude: $150 V_{pp}$,
capacitor temperature: 106.7°C .

Figure 6.9: Thermal images of the electrical enclosure for the RF funnel. In focus (marked by the crosshairs) is the temperature measurement of one of the two series capacitors that fails when the RF funnel is operated at amplitudes greater than $125 V_{pp}$.

optimal SPIG bias voltages for maximum ion transmission were determined for different inlet pressures and RF funnel exit aperture bias voltages. Figure 6.10 shows heatmaps of the ion counts measured at CEM1 roughly centered around the global maxima. The ion counts were measured as a function of the RF funnel exit-aperture potential and the DC bias applied to the SPIG electrodes, for various inlet pressures.

The operating values for both biases are chosen from the region of the parameter space that yields the maximum ion counts. The data confirmed the dependence of the energy of ions entering the SPIG on the funnel chamber pressures, which is in turn proportional to the applied GAR pressure at the inlet. Higher inlet pressures enable ions to overcome

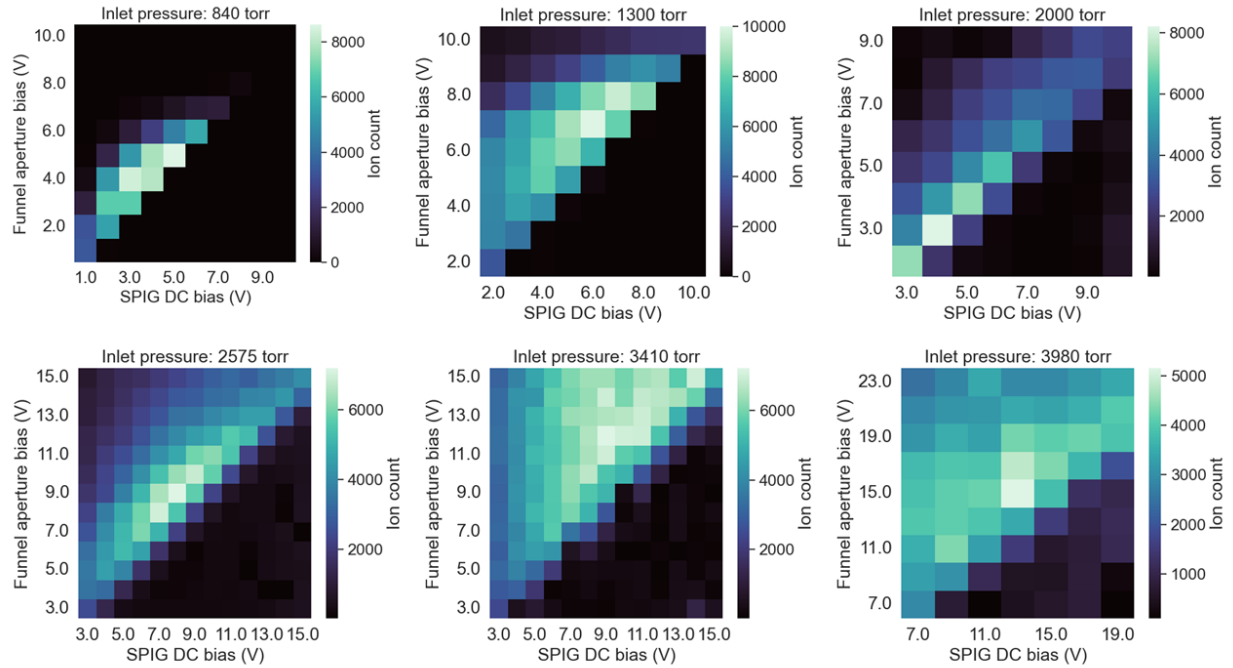


Figure 6.10: Ions extracted from the SPIG at various inlet pressures and at constant RF amplitudes for the RF funnel and SPIG. Ion counts were measured as a function of bias voltages of the SPIG electrodes and the RF funnel exit aperture. For SPIG bias voltages greater than the aperture bias, a sharp decrease in ion transmission was observed resulting from a fraction or all ions being propagated backwards after losing their kinetic energy.

bias potentials above 20 V, providing access to higher-energy ions that can be beneficial for optimizing downstream ion transport. The voltage configurations where the SPIG bias voltage is greater than the aperture bias are excluded due to backflow of ions, as is confirmed through the diagonal feature observed in the shown data.

With the operating regimes of the RF funnel and SPIG established, the next steps in developing the Ba-tagging setup is to characterize the performance and key operating parameters of the LPT in preparation for receiving ions from the RF funnel and forming

ion bunches for mass measurements with the MRTOF-MS. The next chapter shifts focus to the LPT, outlining its role within the overall system and presenting results from its commissioning.

Chapter 7

Ion Identification System: Commissioning and TOF Studies

The subsystem following the RF funnel in the ion extraction scheme is the LPT. Previous studies with the RF funnel determined that the ions extracted from GXe were dominated by ionic and molecular Xe species [121, 124]. These ion extraction studies helped demonstrate the performance of the RF funnel, but to demonstrate viability for Ba-tagging, additional instrumentation with high efficiency and resolving power is required, namely the LPT and the MRTOF-MS. The main purpose of the LPT is to allow for the filtering, cooling, bunching, and in the future trapping required to identify Ba ions using laser fluorescence spectroscopy. This chapter discusses the LPT subsystem and its operation for ion trapping, bunching, and timing measurements. Section 7.1 provides an overview of the LPT design, while Sections 7.2 and 7.3 explore the MRTOF-MS subsystem and its operation alongside with the LPT, respectively. Section 7.4 then presents results

from commissioning studies, including MRP measurements of the QMF, ion bunching performance, and TOF measurements of bunched ions with the MRTOF-MS.

7.1 The Linear Paul Trap Subsystem

The LPT subsystem is composed of four key sections, as illustrated in Figure 7.1: a quadrupole bender and ion assembly for supplying ions; a QMF for selectively transporting ions with masses of a selected range; a precooler differential pumping stage; and an ion cooler and buncher, collectively referred to as ion cooler and buncher (ICB). While confined in the ICB, ions are cooled to form a well-defined ion bunch which can be ejected. After ejection from the buncher, the ion bunch passes through a drift tube, where the applied potential is pulsed to tune the ion bunch energy prior to injection into the MRTOF-MS.

7.1.1 Design of the Vacuum System

Operation of the LPT subsystem relies on efficient ion transport and ion cooling capability. The subsystem is nominally maintained at high-vacuum pressures using three turbo molecular pumps installed on the CF crosses housing the quadrupole bender, the QMF and the ICB. Figure 7.2 shows a schematic of the complete LPT vacuum system. A mass flow controller¹ (MFC001) is used to supply helium buffer gas directly into the cooler. Pressure inside the cooler is measured through a pressure transducer (BPT001) installed on a

¹GM50A series, MKS Inc.

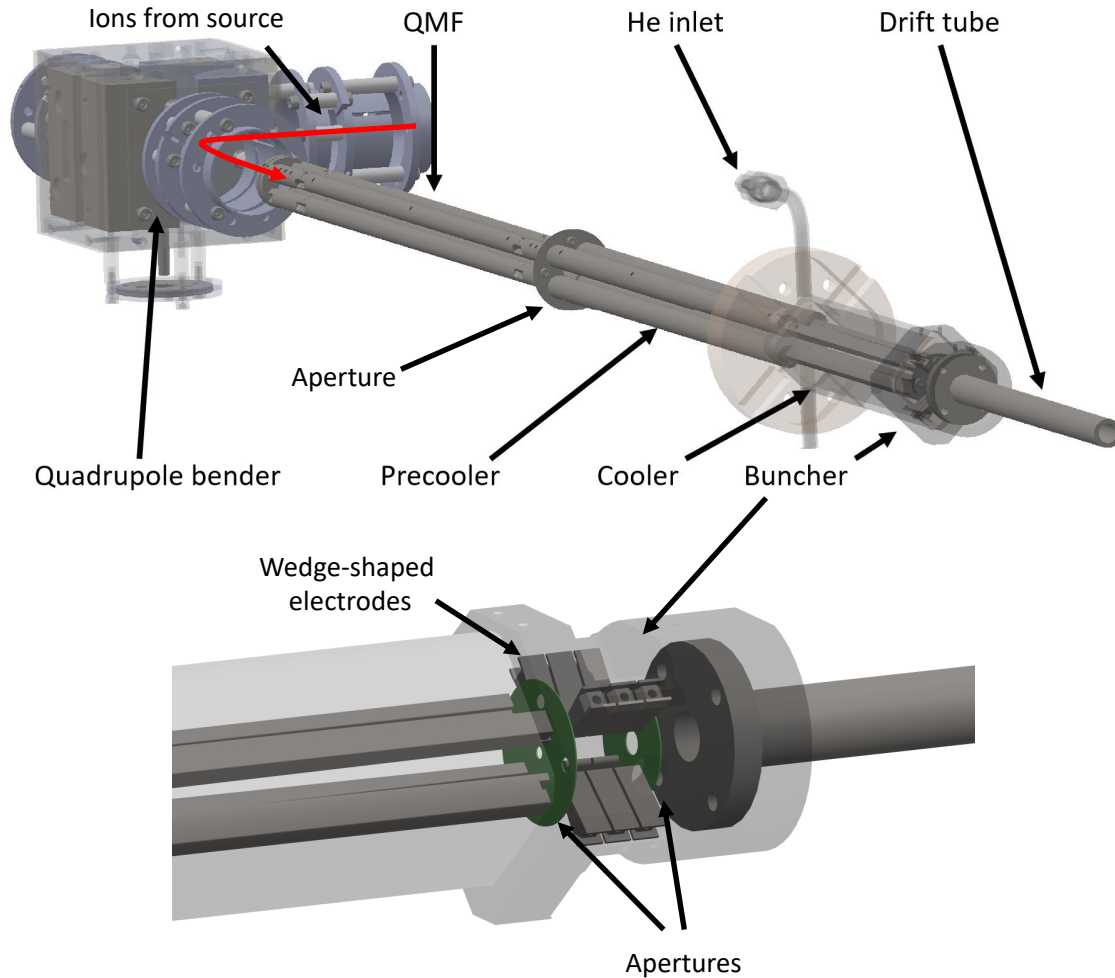


Figure 7.1: Rendering of the LPT subsystem illustrating its various components: the quadrupole bender; the QMF; the ICB which consists of the pre-cooler, cooler and buncher. A zoomed-in view highlights the segmented wedge-shaped buncher electrodes, alongside the entrance and exit apertures (shown in green) that control the entry and exit of ions.

stainless steel tubing connecting directly to the cooler. Flow limiting apertures on either side of the cooler help regulate the flow of gas and maintain the pressure inside the cooler. The purpose of the pre-cooler is to act as an ion guide and enable differential pumping

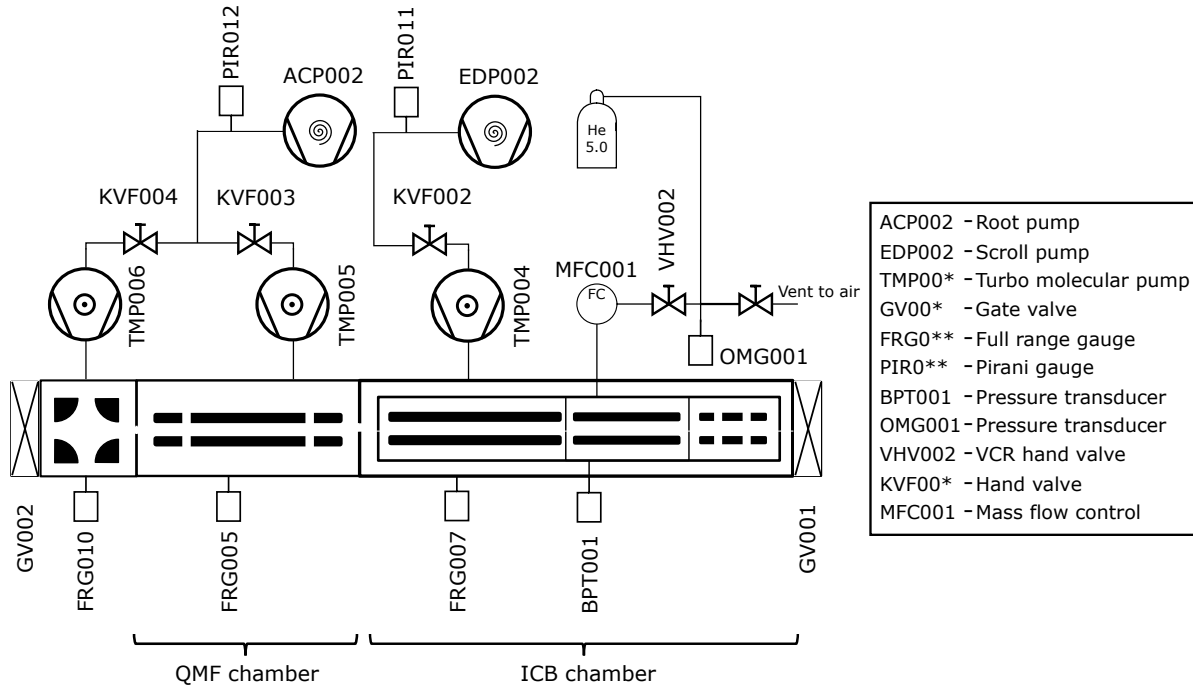


Figure 7.2: Schematic of the LPT vacuum system. Helium is supplied to the ICB through a mass flow controller (MFC001), and the resulting pressure is measured by BPT001, which is connected directly to the cooler via a stainless steel tube. The helium exiting the cooler flows through the buncher and precoolers before being pumped out via TMP004. The LPT can be isolated from the other subsystem by the gate valves on either side during maintenance or ion source replacement.

between the QMF, which requires high vacuum for operation, and the cooler, which is maintained at pressures of order 0.1 mbar.

In the ICB, the ions are first cooled and stored in the cooler, before being transferred to the buncher. While in the buncher, ions continue to cool further through collisions with buffer gas coming from the cooler, before being ejected as an ion bunch into the MRTOF-MS. Each section of the vacuum system is fitted with a full-range pressure gauge for monitoring

chamber pressures. The vacuum system has been leak tested at multiple instances and is able to reach vacuum beyond 10^{-9} mbar.

7.1.2 Ion Trap Electronics

The key drivers for the operation of the LPT subsystem are RF potentials for radial confinement of ions and DC potentials for axial control. The choice of RF frequency to operate the QMF and ICB is influenced by two key factors. First are the trajectory parameters (described in Chapter 4) to ensure a stable ion path. Second comes from the power capacity of the RF amplifiers² used. Emphasis is placed on maximizing the RF frequency to better approximate the conditions assumed in the theoretical framework of Chapter 4, which treats the quadrupoles as infinitely long. At sufficiently high RF frequencies, the ion motion can be described using a pseudopotential approximation, since the ions experience many RF cycles during their transit and the fast micromotion averages out to a time-independent effective potential [135].

Considering the above factors, the operation frequency for the QMF was set to 750 kHz, which gives access to a large ion mass acceptance range while ensuring undistorted RF signal at higher amplitudes. For better power transfer, the impedance of the QMF along with RF circuitry, similar to that shown in Figure 6.4, was measured using a vector network analyzer (VNA) and made to match to a $50\ \Omega$ load equivalent at 750 kHz, similar to the RF funnel

²QMF: Mini-circuits LZY-22+, ICB: ENI 325LA

and the SPIG. 1 MHz was chosen as the operating frequency for the ICB but in this case, no impedance matching was required due to the higher capacity of the RF amplifier used.

In addition to the RF circuitry, fast-switching voltage switches are used for the buncher electrodes to allow for the loading and ejection of ions and ion bunches, respectively. These switches support short rise times on the order of 50 ns, which is required to minimize losses during transfer and ejection of ion bunches. After ejection, the ion bunch is accelerated from ~ 100 eV to > 1 keV in a pulsed drift tube by switching its potential from -225 V to $+1.1$ kV. The accelerated ions are subsequently confined within the MRTOF-MS, where a TOF measurement is performed to determine their mass-to-charge ratio.

7.2 Multiple Reflection Time-of-Flight Mass Spectrometer

The MRTOF-MS is the final subsystem of the Ba-tagging setup designated to identifying extracted ions and performing systematic studies on ions extracted from the RF funnel. The commissioning study of the MRTOF-MS with ions provided from a LAS, bypassing the LPT, concluded with a MRP of 20 000 achieved using Cu ion pulses [125]. Based on SIMION simulations of the MRTOF-MS, the bunched ions from the LPT are expected to enable an MRP of about 100 000 which will be sufficient to resolve $^{136}\text{Ba}^+$ from its primary isobaric background, $^{136}\text{Xe}^+$.

The MRTOF-MS subsystem includes three main sections: a quadrupole bender similar

to the LPT for supplying ions; steering electrodes and Einzel lenses (shown in Figure 5.2) to focus ions into the MRTOF-MS through a collimating aperture; and finally two sets of mirror electrode assemblies to trap ions. The mirror electrode assemblies consist of six ring-shaped electrodes each. Four of the six electrodes are used for refocusing ions after reflection from the potential barrier formed by the two outermost electrodes. In the entrance mirror, these two electrodes are controlled using two three-state switches³ to operate in injection, TFS, or isochronous modes. Their counterparts in the exit mirror electrode assembly are controlled with two two-state switches to switch between isochronous and ejection modes. Details of the voltage switching are described in the next section. The MRTOF-MS design includes a mass selector located at the center of the drift space. This selector is intended to remove ions outside the mass ranges being measured by applying a pulsed transverse field. Ions impacted by this field, which is active only for a finite duration (few μs), are deflected onto unstable ion trajectories. This ensures that the ions of interest are not affected by interference from these leading/lagging ions or ions outside of the measurement range in subsequent revolutions. The MRTOF-MS is maintained at UHV ($< 10^{-8}$ mbar) to minimize collisions with background gases that would impact the MRP and increase ion losses, particularly at higher numbers of revolutions.

For tuning purposes, three out of the four CEM devices shown in Figure 5.8 are located at various locations inside the MRTOF-MS subsystem. CEM2 is located at the MRTOF-

³Bespoke Scientific Electronics HV switches

MS quadrupole bender, and can be moved into beam path via a stepper-motor-controlled linear actuator⁴. Similarly, CEM3 is installed on an actuator downstream of the collimating aperture to facilitate tuning of the steering and focusing electrodes. CEM4 is located at the far end of the MRTOF-MS and is used to record the TOF of ions. These detectors play a crucial role in tuning of the Ba-tagging system, and results from their measurements are presented later in this Chapter.

7.3 LPT-MRTOF Operation

Ions injected into the LPT are first filtered in the QMF before being stored in the cooler. Since the cooler and buncher can only hold a limited number of ions, filtering ions first with the QMF helps prevent overloading and avoids downstream losses caused by space charge effects. Ions exiting the QMF pass through the precooler and are continuously accumulated in the cooler near the entrance aperture of the buncher, before being transferred at regular intervals. Ion transfer is achieved by briefly lowering the entrance aperture potential (for a few ms), allowing ions near the aperture to enter the buncher, where they are trapped via buffer gas cooling. Voltage switches are used to control all time-varying DC biases applied to the buncher entrance and exit apertures, as well as the buncher quadrupole segments. The timing of all the voltage switches is controlled through square pulses supplied by an field programmable gate array (FPGA) unit. Figure 7.3 shows a sample of the FPGA signal

⁴HTL-275-2, Linear Feedthrough with DC stepper motor, Accuglass Products Inc.

LPT-MRTOF Timing Diagram

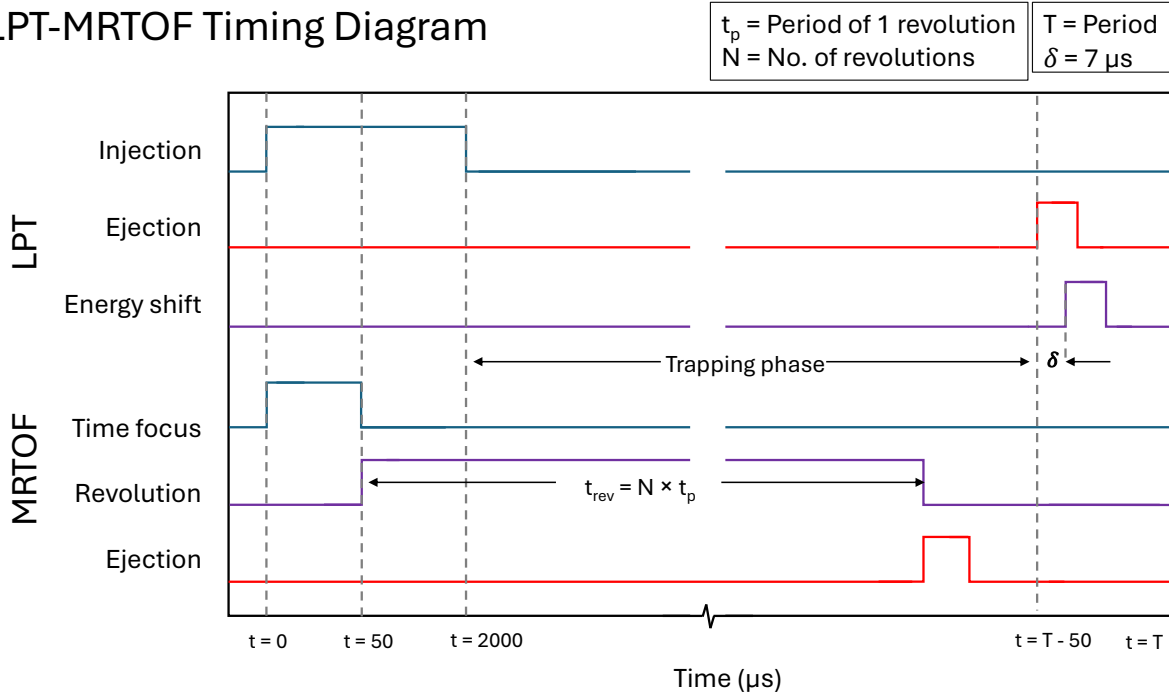
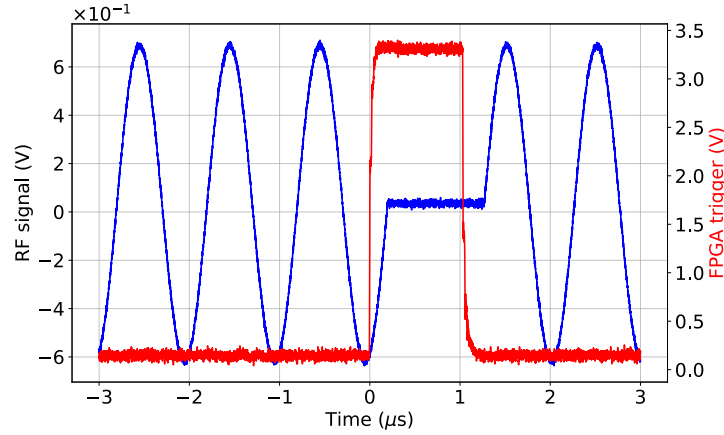


Figure 7.3: Timing diagram of the Ba-tagging system. Eight FPGA channels are used to operate the Ba-tagging system, including one channel dedicated to triggering data acquisition and another for synchronizing the ICB RF phase with the FPGA. The pulses shown correspond to control signals governing the loading of ions in the buncher and the ejection of ion bunch into the MRTOF-MS. The pulse durations represent the time each voltage switch remains in a given state. This includes the three-state switches controlling the entrance mirror of the MRTOF-MS, which are actuated through a combination of the MRTOF injection and time-focus pulses. Due to the logic adopted here, the entrance electrode potentials are held at ground outside the periods corresponding to isochronous and TFS revolutions, thereby allowing ions ejected from the LPT to enter the MRTOF-MS.

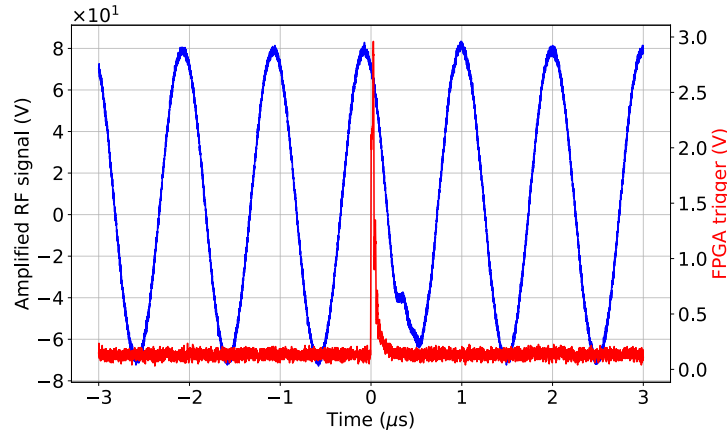
level output to the LPT and the MRTOF-MS for a specific cycle period T . At the end of the injection pulse, the entrance aperture potential is raised to prevent further ion injection and

to allow the trapped ions to cool before ejection into the MRTOF-MS at the end of the cycle. This process was previously illustrated in Fig. 4.8 using the example of axial potentials in the buncher. Similarly, the electrode potentials in the entrance mirror of the MRTOF-MS are switched such that the electrodes are held at ground potential prior to the LPT ejection pulse, and then switched to bias potentials of the TFS mode once the ion bunch reaches the center of the MRTOF-MS. After the first revolution, which corrects the time focus of the ion bunch, the electrode potentials are set to values corresponding to the isochronous mode for subsequent revolutions until ejection, where the TOF spectrum is acquired.

The RF phase at the moment of ion ejection from the buncher influences the properties of the extracted ion bunch. To ensure consistency, the phase of the RF potential is synchronized with the FPGA clock cycle by resetting the waveform generator output to a user-defined phase before the start of each cycle. Figure 7.4a shows the output of the waveform generator and the transistor-transistor logic (TTL) signal provided by the FPGA for the reset. The output of the waveform generator is set to zero for the duration of the TTL signal, after which it resumes with the user-defined RF phase. Figure 7.4b shows the amplified RF potential supplied to the ICB together with the TTL signal from the FPGA. Here, the duty cycle of the signal is set to the minimum possible value to reduce instability in ion confinement in the cooler during the RF phase reset. Any distortion in the RF signal due to the reset disappears within two oscillation periods ($2\mu\text{s}$). After ejection, ions are accelerated a second time in a pulsed drift tube before entering the MRTOF-MS. In the time it takes for ions



(a) RF signal from the waveform generator (blue) and the TTL signal (red) provided as input for channel reset. While the TTL is high, the phase of the RF signal is held at a set value, ensuring it resumes oscillation from a known phase once the reset ends.



(b) Amplified RF signal supplied to the ICB (blue) and the TTL signal (red). Here, the duty cycle of the TTL is set to the minimum possible value to reduce ion losses during reset process.

Figure 7.4: The RF signal is reset using a TTL signal supplied by an FPGA. This reset locks the RF phase at the time of ion bunch ejection, ensuring efficient transfer of ion bunches to the MRTOF-MS.

to reach the MRTOF-MS center, ions are once more transferred from the cooler into the buncher restarting the cycle. The period of this cycle is primarily dependent on the number

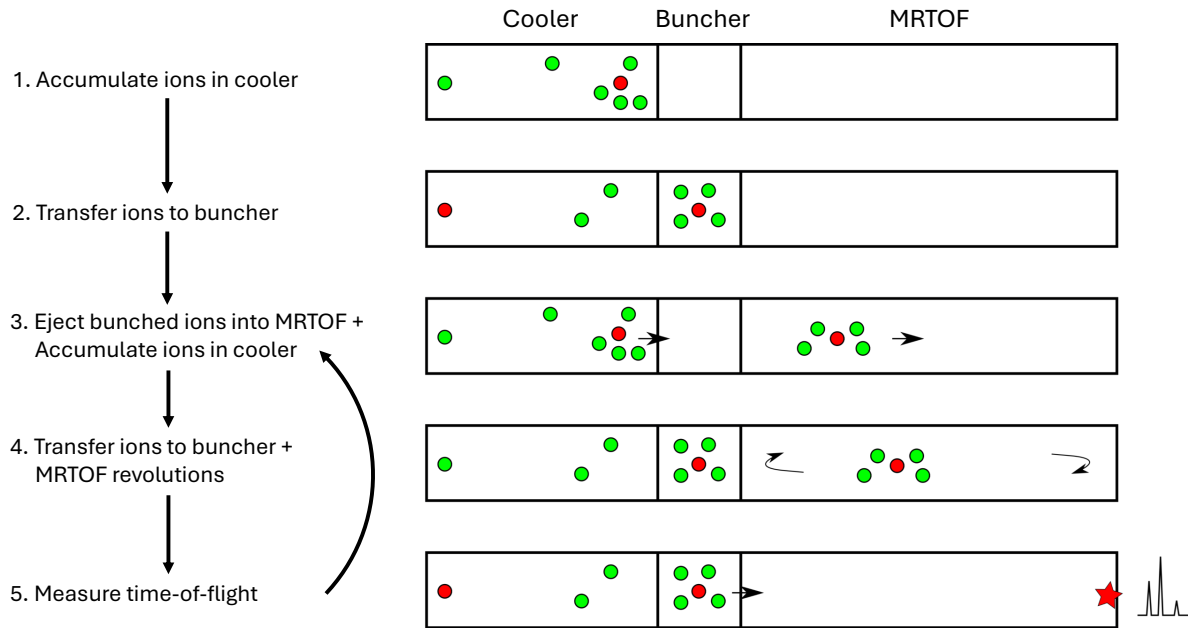


Figure 7.5: Schematic of LPT and MRTOF-MS operation showing the trapping scheme. Ions from LPT are ejected into the MRTOF-MS followed by reloading the buncher with next batch of ions. Ions continue cooling for the duration of one MRTOF-MS cycle after which they are ejected again to repeat the process. The continuous collection of ions in the cooler ensures ions are not lost during the loading and ejection steps.

of revolutions required for the MRTOF-MS mass measurement. During the MRTOF-MS revolutions, ions in the buncher continue to cool down until the next ejection step. Ions in the MRTOF-MS are detected using CEM4 and the TOF data is recorded using a digitizer⁵. Figure 7.5 shows a step-by-step walkthrough through of a full measurement cycle, starting from the first time ions are collected in the cooler leading up to periodic TOF measurements of the bunched ions in the MRTOF-MS.

⁵CAEN DT5730 digitizer

7.4 Commissioning of the Linear Paul Trap

Commissioning of the LPT was carried out using a Cs thermal ion source, which provided a well-characterized ^{133}Cs beam for tuning ion transport in the ^{136}Ba mass range. This section presents the commissioning studies and performance results of the LPT subsystem, start with the MRP measurement of QMF and followed by the full ion transport, bunching and TOF measurements with the MRTOF-MS.

7.4.1 QMF Resolving Power Characterization

The general characteristics of the QMF were tested as part of a previous study [150] which successfully reproduced the stability-parameter phase space for ion transmission, as theoretically predicted and confirmed in SIMION simulations of the QMF. A key requirement from the QMF is to resolve $^{136}\text{Ba}^+$ from potential background ions that could negatively impact the trapping efficiency of the ICB. An $\text{MRP} > 80$ was determined to be sufficient to filter such background ions using the QMF [116]. To verify this, a thermal ion source was used to deliver a stable beam of ^{133}Cs to the QMF. As per the scheme described in Chapter 4, the MRP of the QMF can be determined by varying the RF amplitude (V) and differential DC bias (U) such that the ratio ($s = a/q = 2U/V$) is kept constant as shown in Equation 4.10.

Due to the shape of the stable trajectory phase space which peaks at $q = 0.706$, the

resolution of the mass peak increases for larger values of s , up to the maximum possible slope:

$$s_{max} = a_p/q_p = 0.237/0.706 = 0.336.$$

Figure 7.6 shows the ^{133}Cs mass peak for different slopes of the scan line. The ion energy for the measurement was set to 50 eV by biasing the source to 50 V, the QMF RF frequency was 750 kHz and the entire QMF was biased to -5 V to improve ion injection. The ion current was measured using a digital multimeter and the data was averaged over a 5 s period for each data point. Between each measurement, another 5 s delay was given for the potentials to stabilize before the next measurement. For each scan line, the MRP was computed using the peak location and FWHM of a gaussian distribution fit to the data based on Equation 4.10.

The last plot in Figure 7.6 exceeds the minimum requirement for the QMF, at which point most ions with masses outside $m = [134.5, 137.5]$ u can be filtered out, allowing only $^{136}\text{Ba}^+$ and other isobaric ions like $^{136}\text{Xe}^+$ to transfer into the ICB. Based on the results, an even higher resolving power should be achievable by biasing the QMF electrodes closer to the ion energy to maximize the number of RF periods encountered by the transiting ions.

7.4.2 Ion Trapping and Bunching in the LPT

With the QMF performance fully explored, we now turn to ion trapping and bunching in the ICB and present measurements that map out the operating conditions required for reliable ion capture, storage and ejection. To perform ion trapping, ions exiting the QMF

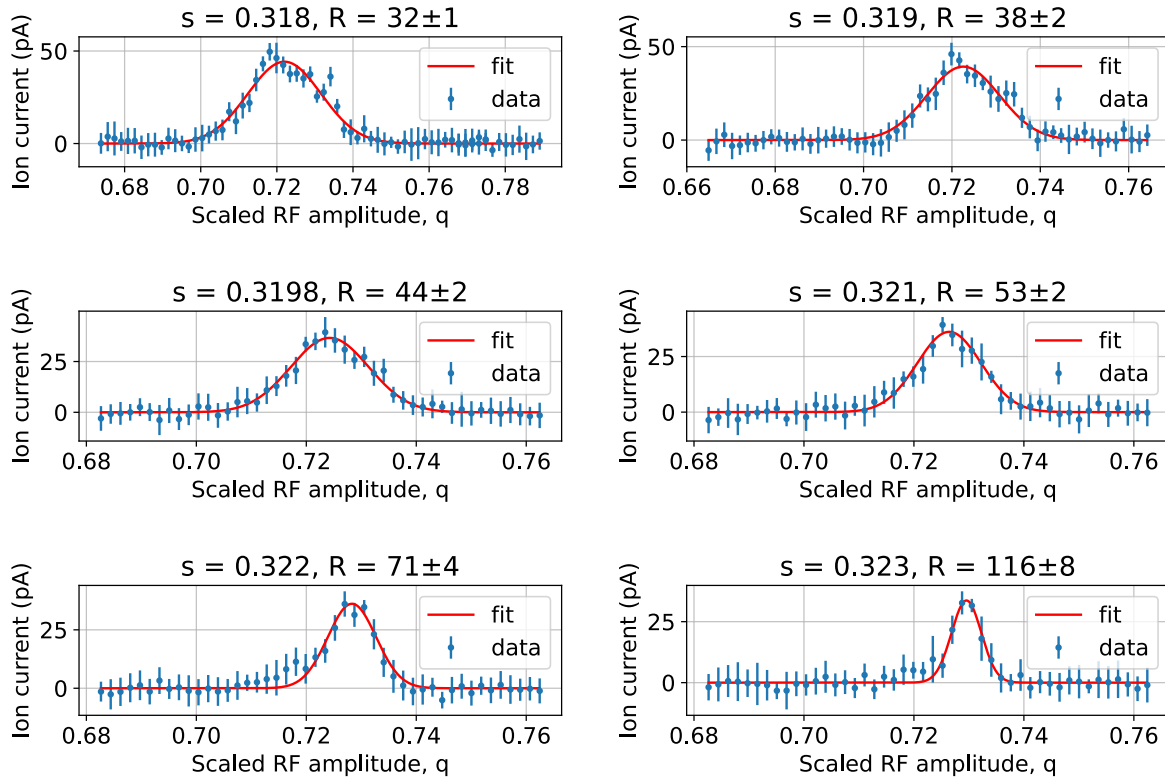
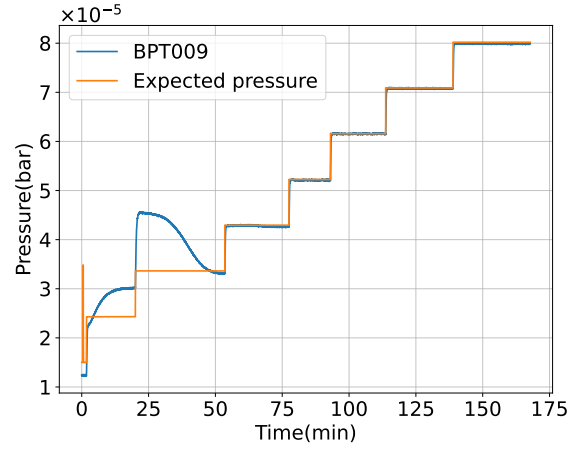


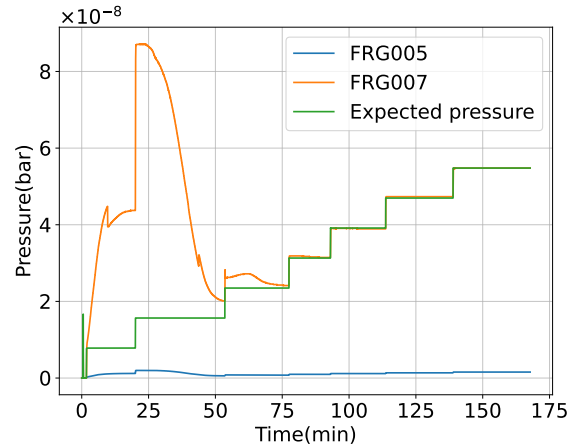
Figure 7.6: QMF mass scan of ^{133}Cs ions for different values of scan line slope s . The DC potential is varied proportional to the RF amplitude as $s = a/q = 2U/V$. Each data point corresponds to a 5 s average of ion current and (in red) a gaussian distribution used to determine the position and FWHM of the mass peak.

are first cooled down and temporarily stored in the cooler using He as the buffer gas. He gas (Grade 5.0) was deployed into the cooler through a mass flow controller and the pressure response of the system was studied as a function of different flow rates. Figure 7.7 shows the measured and expected pressures calculated using known system conductance and throughput of the turbo-molecular pumps⁶ used in the LPT subsystem. The

⁶Pfeiffer HiPace 700



(a) Measured (BPT009) and calculated pressure inside the cooler as a function of He flow rate.



(b) Measured (FRG007) and calculated pressure in the vacuum chamber housing the cooler as a function of He flow rate. FRG005 measures the pressure inside the QMF which shows only a marginal increase in pressure during ICB operation ($\sim 2.5 \times 10^{-9}$ bar).

Figure 7.7: Buffer gas pressure response of the LPT vacuum system. The stair case pattern seen here comes from the increase in He flow made in increments of 2 sccm. The pressure in the system takes time to equilibrate as is seen from the initial deviation from expected pressure. Once the pressures equilibrate, the system response follows the expected pressure values and remains stable between subsequent increments in He flow.

increments in expected pressure seen here correspond to the increase in He flow made in increments of 2 sccm up to 14 sccm. It was observed that the pressure response of the system initially requires up to one hour at low flow rates to stabilize, after which it is very quick to respond to changes. During typical operations, this stabilization period is significantly reduced to less than ten minutes by running the system at high flow rates of 20–25 sccm from the very beginning. Ion–buffer gas interactions in the cooler were modeled in SIMION using a hard-sphere collision model. These simulations identified an optimal cooler operating pressure on the order of 0.1 mbar [150]. This corresponds to a flow rate of 25 sccm, which is used for all measurements presented in this subsection, unless specified otherwise.

To prepare the LPT for ions from the SPIG, which, as shown in Figure 6.10, are typically delivered at SPIG DC potentials of ~ 0 –25 V, the system was tuned using a 10 eV Cs ion beam. The timing scheme previously shown in Figure 7.3 was used to successfully bunch and transport ions to the MRTOF-MS in combination with DC and RF voltages values for ion trapping listed in Tables B.1 and B.2. The bunched ions were detected using the CEMs installed downstream of the LPT.

The signals from ion bunch detection with the CEMs are saved as waveforms. Samples from 10 000 such waveforms are collected from the CEMs using a digitizer⁷ and used to populate TOF histograms. Here, a sample refers to an individual ADC value that

⁷CAEN DT5730 digitizer

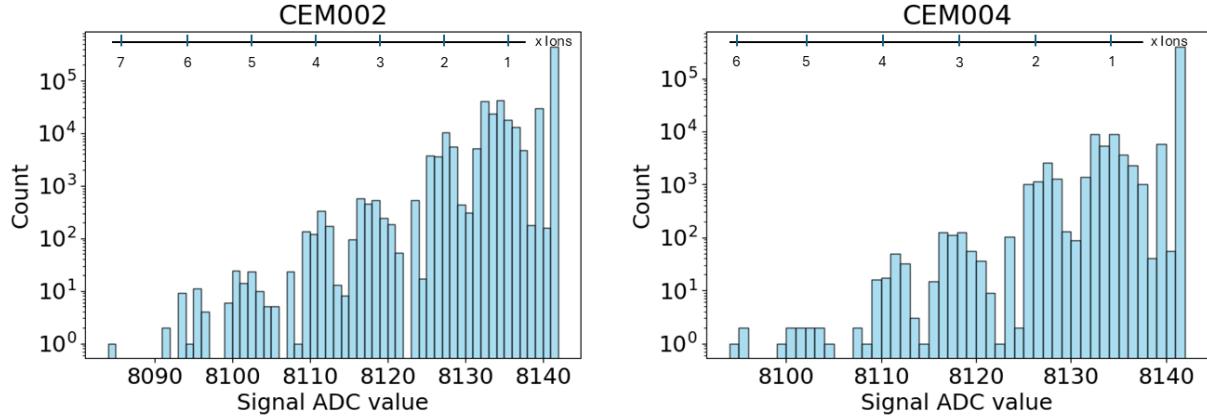


Figure 7.8: ADC amplitude distribution observed from CEM2 and CEM4. The histograms are truncated to include only samples with amplitudes exceeding the respective signal thresholds. The inferred ion count corresponding to each ADC amplitude region is indicated in the annotations.

corresponds to a 2 ns acquisition interval. The signal amplitude is converted from ADC values to ion counts for each sample within a waveform. Figure 7.8 shows histograms of the ADC values recorded from CEM2 and CEM4 during these measurements. Using CEM2 as an example, the ADC amplitudes exhibit peaks separated by regular intervals of 7 ADC levels, indicating that a change of approximately 7 ADC levels corresponds to one ion within a given sampling interval. This calibration factor is used to convert ADC values to ion counts. For instance, if a sample has an ADC value of 8125 and the signal threshold is 8140, the estimated number of ions in that sample is $(8140 - 8125)/7 \approx 2 \text{ ions}$ ⁸. To determine the threshold value, each CEM was read out without any ion input to obtain the baseline noise distribution. Figure 7.9 shows the mean ADC and threshold values for the

⁸Here, the signal value is below the signal threshold since ion peaks appear as negative going peaks.

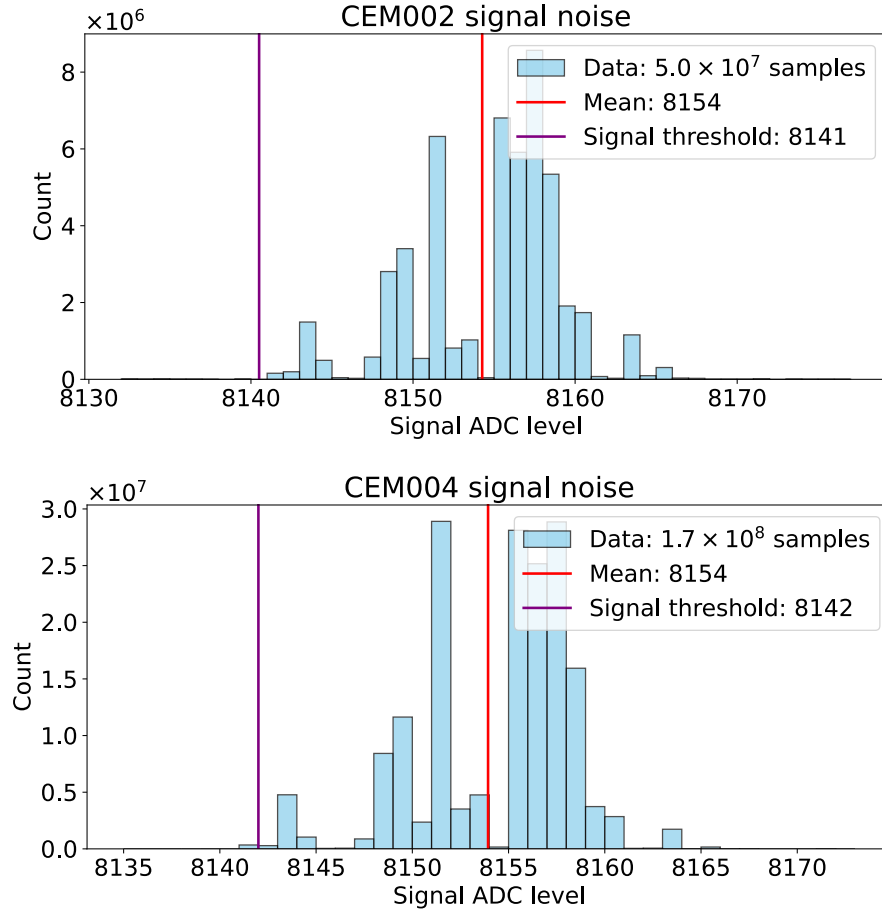
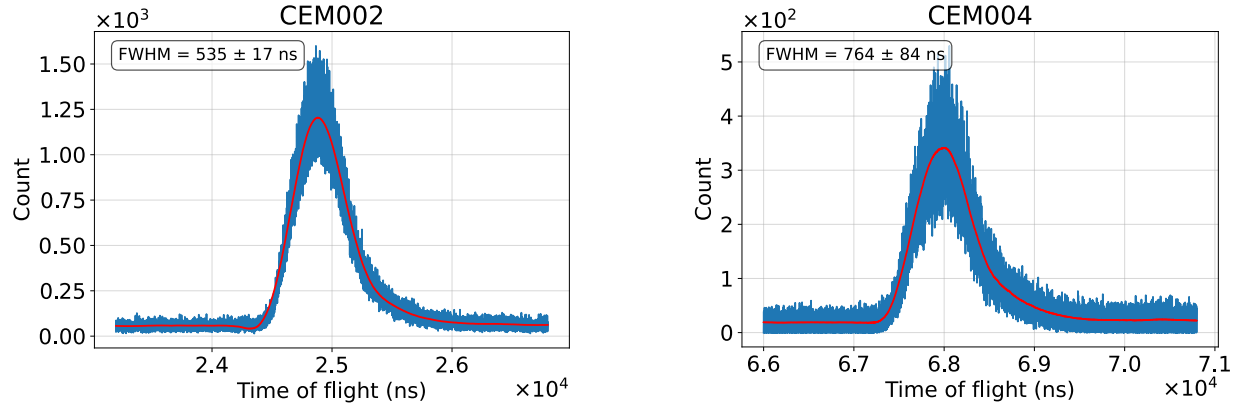


Figure 7.9: ADC amplitude distribution from CEM2 and CEM4 taken without bunched ions. The signal threshold is defined as three standard deviations below the mean, shown here by the purple vertical lines.

respective CEMs. Here, the signal threshold is defined as three standard deviations below the mean of this distribution. Figure 7.10 shows the TOF histograms of the ion bunches arriving at CEM2 and CEM4, respectively. A Savitzky–Golay filter is applied to the histograms for smoothing prior to calculating the FWHM [164]. An increase in the FWHM was observed from CEM2 to CEM4, accompanied by a reduction in ion count.



(a) Sample TOF spectrum of bunched ions on CEM2 located downstream of the LPT.

(b) Sample TOF spectrum of bunched ions on CEM4 located downstream of the MRTOF-MS.

Figure 7.10: Bunched ions of energy ~ 1.1 keV detected inside the MRTOF-MS using CEM2 and CEM4. Samples from 10 000 waveforms were accumulated to populate the TOF histogram. These histograms were then used to determine the ion energy and TOF spread of the bunched ions immediately after ejection from the buncher (CEM2) and after transit across the length of the MRTOF-MS (CEM4).

The buncher performance was studied through measurements of ion bunches detected at CEM2 in order to optimize for a high ion count per bunch and a low FWHM. The trapping capacity of the buncher was investigated as a function of the buffer gas pressure inside the buncher and the transfer time. The results are shown in Figures 7.11. The pressure inside the ICB is proportional to the buffer gas flow rate as was demonstrated in Figure 7.7. The ion count per bunch was found to be proportional to the buffer gas pressure when tested for buffer gas flow over the range of 2–40 sccm. The sharp decrease in the TOF FWHM is likely resulting from improper cooling at very low buffer gas pressures. In contrast, the ion count per bunch was seen to be inversely related to the transfer time. The TOF FWHM

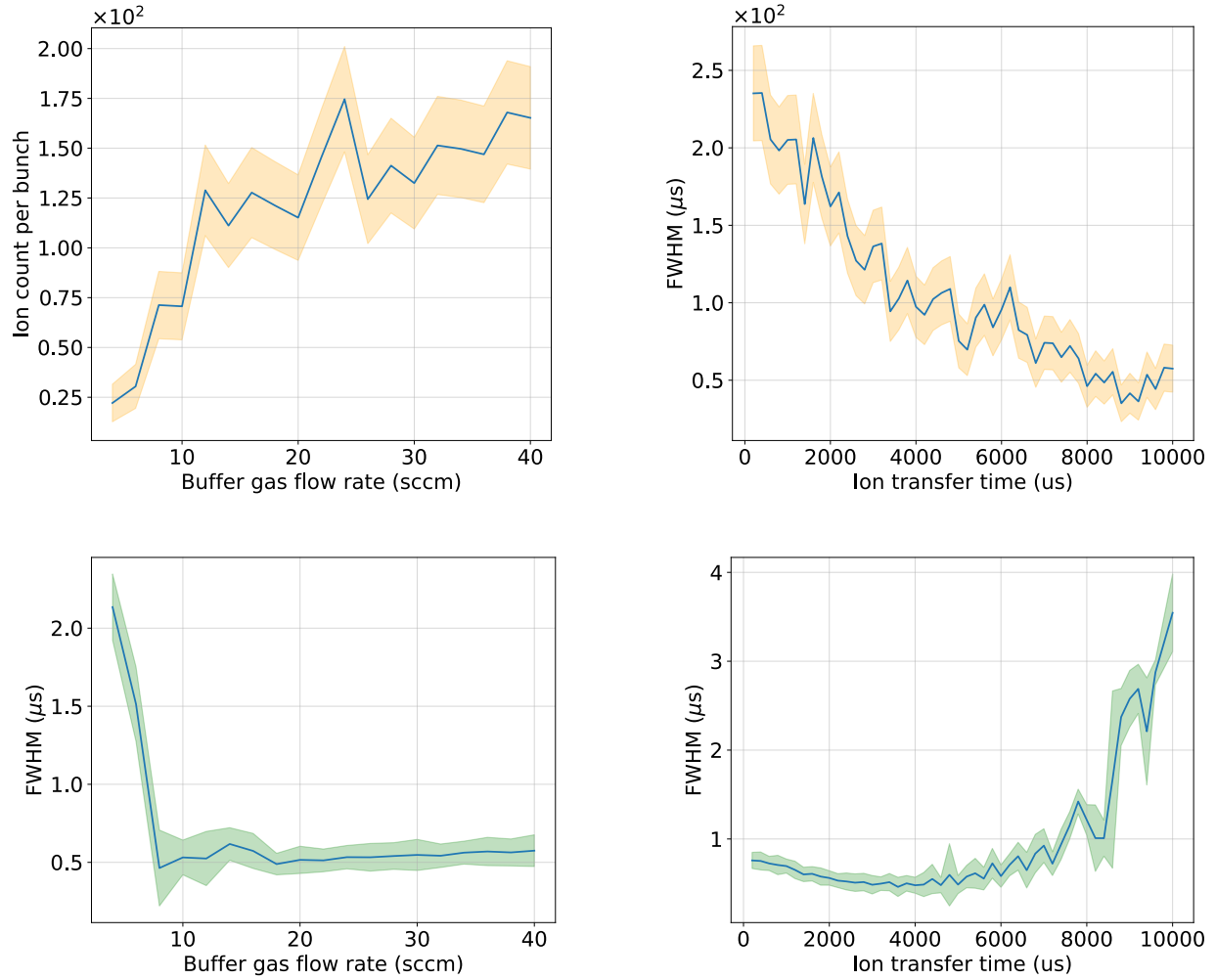


Figure 7.11: Effect of buffer gas flow rate and transfer time on the ion bunch. (Top left) The ion count per bunch increases with higher buffer gas pressures and (top right) reduces with increases transfer period. (Bottom left) The FWHM of the ion TOF shows a decrease at higher buffer gas pressures while (bottom right) showing an increase with higher transfer time after reaching a minimum at around 4000 μs .

corresponding to the different transfer time durations shows a minima at 4000 μs before eventually increasing as transfer time approaches the cycle time at 10000 μs . As the transfer

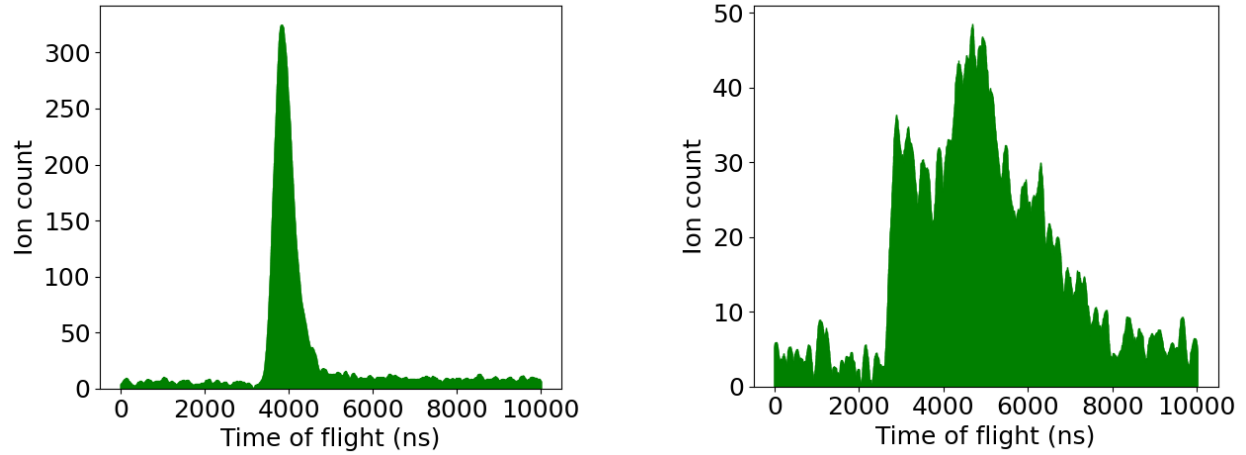


Figure 7.12: TOF histograms of ion bunches cooled with 4 ms ion accumulation (left) and with continuous accumulation for 10 ms until ejection (right). The histogram from continuous accumulation highlights the need for trap isolation, showing a visibly lower ion count and excessive dispersion arising from improper ion cooling.

time approaches the cycle time, multiple peaks begin to appear in the TOF histogram due to insufficient cooling of the transferred ions prior to ejection. Figure 7.12 compares the TOF histogram of ions accumulated for 4000 μs and then cooled for 6000 μs with that of ions continuously accumulated for the entire cycle time of 10000 μs . This observation motivates the use of a two-stage trapping scheme involving pre-trapping and accumulation in the cooler, followed by trapping in the buncher, as illustrated in Figure 7.5. Similarly, Figure 7.13 shows the ion bunch characteristics as a function of the RF phase at ejection, and the total time ions are stored inside the buncher before ejecting into the MRTOF-MS. The RF phase shows two maxima at roughly 30° and 210° , but with a matching increase

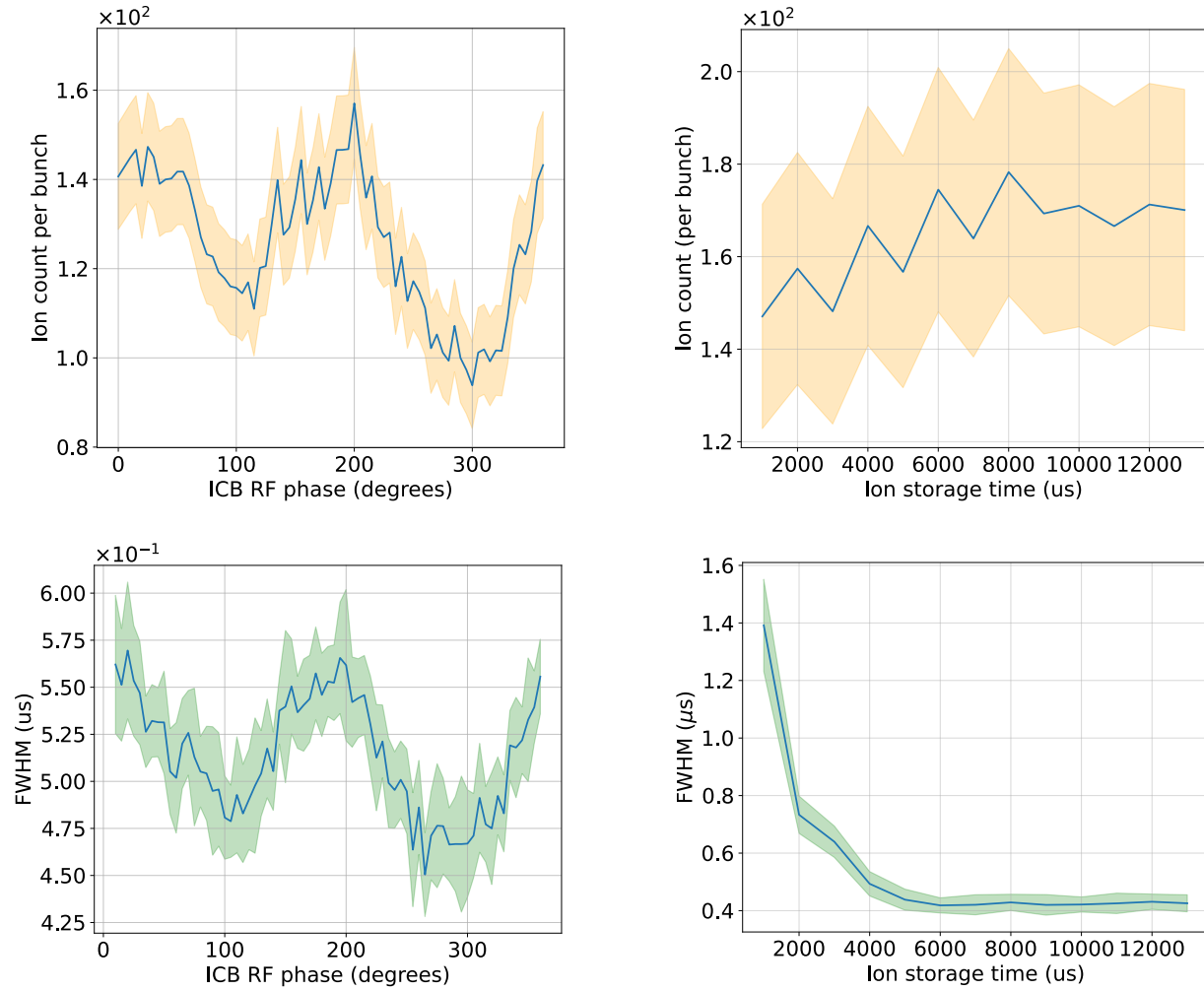


Figure 7.13: Effect of ejection phase and storage time on the ion bunch. (Left) The RF phase at ejection affects both the detected ion count and the TOF FWHM, producing proportional changes in these quantities. (Right) The ion storage time shows a decrease in the TOF FWHM that becomes constant beyond 6000 μs .

in FWHM. FWHM exponentially decreases for larger storage times as is expected with improved ion cooling which also results in better ion transport efficiency, reflected in the marginal increase seen in the ion count.

The performance of the LPT to filter ions in the QMF and to trap and bunch ions in the ICB was successfully studied through this commissioning campaign. The system is prepared and fully capable to operate using ions from the RF funnel to study the composition of the extracted ions from GAR (and subsequently from GXe).

7.4.3 Time-of-Flight Measurements

Bunched ions from the LPT were successfully detected in the MRTOF-MS following the installation of CEM3 downstream from the collimating aperture (see Figure 5.2). Scanning of electrostatic steerer potentials revealed a misalignment in beam axis of the two subsystems, arising from initially being separate assemblies that were later coupled. After corrections were applied using steerers, ion bunches were successfully detected at CEM4 as was previously shown in Figure 7.10b. The transferred ions were subsequently trapped in the MRTOF-MS to perform TOF measurements for trapping durations spanning up to 180 revolutions, with results shown in Figure 7.14. The electronics, trigger system and general operational stability were tested through TOF measurements of ion bunches trapped. Trapping duration was increased starting from zero isochronous revolutions in increments of ten revolutions. The color of the data points represents the total ion count from the accumulation of 1000 MRTOF-MS cycles. A linear fit was performed to determine the average period of an MRTOF-MS isochronous revolution. It was observed that ion count goes down with higher number of revolutions along with broadening of the

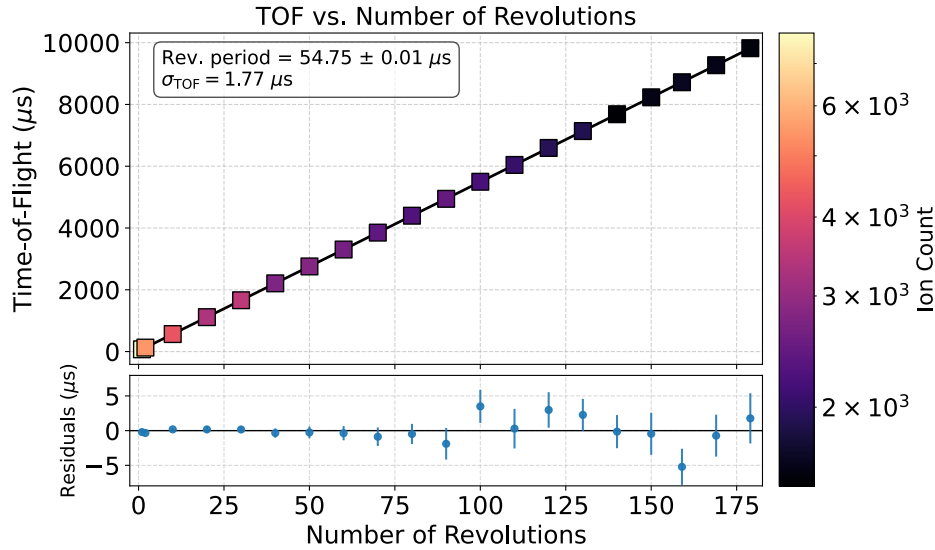


Figure 7.14: Ion bunch TOF measured as a function of number of revolutions. Ion count and FWHM are measured using CEM4 and are shown through the color bar on the right and residual plot at the bottom, respectively. A linear fit is used to extract the period of one revolution which was found to be $54.75 \pm 0.01 \mu\text{s}$.

mass peak as seen from the error bar on the residuals. A drift was observed in the residuals indicating systematic effects possibly arising from drift in mirror electrode potentials, ion source output or temperature fluctuations. Figure 7.15 shows the variation in measured TOF of ^{133}Cs ions over the course of a measurement spanning 150 000 cycles acquired over approximately one hour. The recorded waveforms were grouped into sequential batches, with each batch used to independently determine the TOF. Using this method, the TOF was computed for different numbers of MRTOF-MS revolutions using a batch size of 10 000 waveforms. The analysis was also repeated for the 100-revolution dataset using different batch sizes of 10 000 and 50 000 waveforms. Overall, a drift in the TOF on the order of

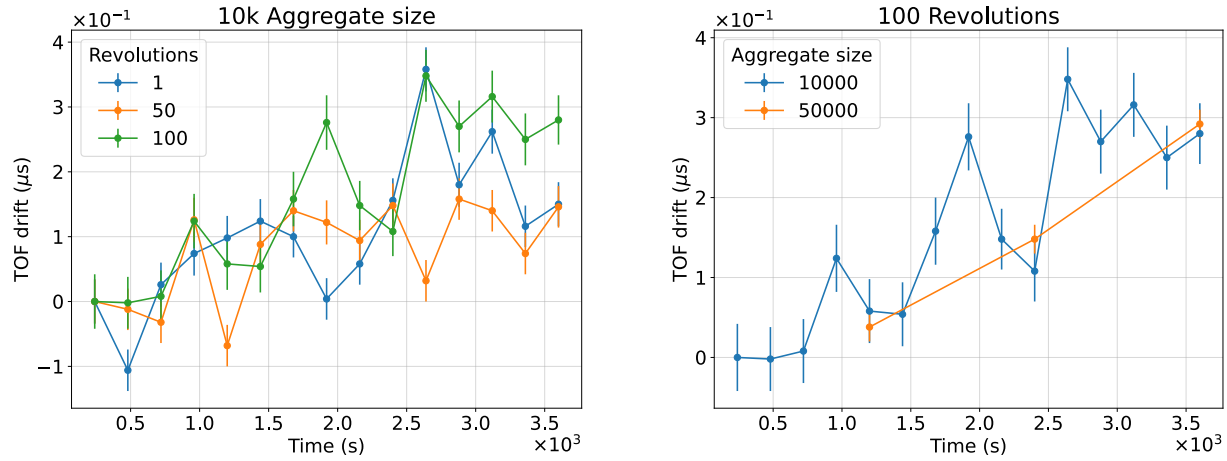


Figure 7.15: TOF drift observed across the measurement for (left) different numbers of revolutions and (right) waveform aggregate sizes. Each data point represents the TOF calculated from a subset of the 150 000 collected waveforms, plotted as a function of their time of occurrence. The drift generally follows a common trend, as observed from the 10 000 and 50 000 waveform aggregates of the 100-revolution dataset, with a total variation of approximately $0.3 \mu\text{s}$ over one hour of data collection.

$0.2\text{--}0.3 \mu\text{s}$ was observed. This drift appears as a broadening of the TOF peak over time and must therefore be corrected. Figure 7.16 shows the final TOF measurement of ^{133}Cs ions taken at 275 revolutions over around an hour of data taking. The drift in TOF discussed in Figure 7.15 was corrected using time-resolved calibration to yield an MRP of 19973 ± 201 [165].

This concludes the commissioning studies undertaken in this thesis to establish a fully operational system capable of performing precision mass measurements of extracted ions. The RF funnel, LPT and MRTOF-MS have each been characterized and demonstrated to operate reliably as integrated components of the overall apparatus. Future work will

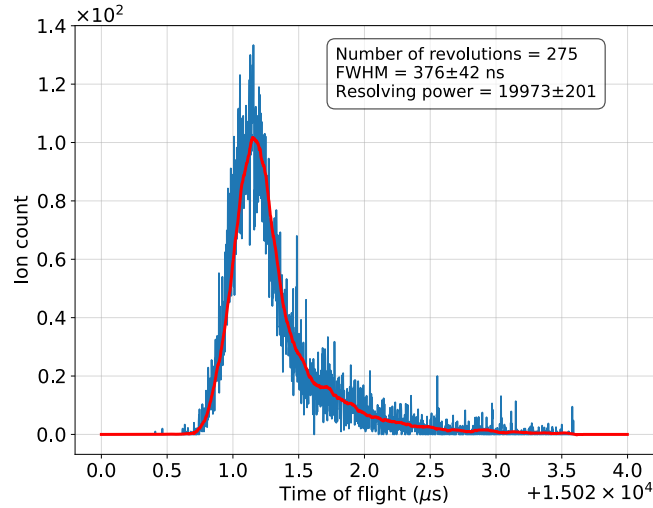


Figure 7.16: TOF measurement of bunched $^{133}\text{Cs}^+$ ions from the LPT with a total TOF of 15.02 ms. The aggregated data are shown in blue, while the drift-corrected TOF spectrum is shown in red. The corrected spectrum was smoothed using a Savitzky–Golay filter prior to measuring the FWHM, yielding an estimated resolving power of 19973 ± 201 after 275 revolutions.

employ sources such as a mixed aluminosilicate source similar to the current Cs thermal ion source or a LAS to further explore the operational range and trapping performance of the LPT with ions beyond the primary ion of interest, ^{136}Ba , thereby broadening the potential applications of the system beyond Ba-tagging. In parallel, ion extraction from GXe using the RF funnel will be carried out in combination with the LPT and MRTOF-MS to demonstrate the complete ion transport and identification scheme. The successful integration of these components will enable the unambiguous identification of extracted barium ions through high-resolution mass spectrometry, representing the next critical milestone toward the realization of a Ba-tagging technique for the nEXO

experiment and its search for neutrinoless double beta decay.

Chapter 8

Discussion and Outlook

Research probing for physics beyond the SM has made significant progress over the past decades. In particular, the discovery of neutrino oscillations demonstrated that at least two of the three known neutrino mass eigenstates possess a non-zero mass, providing clear evidence that the SM in its original formulation is incomplete [14]. The discovery of neutrino oscillations established that neutrino flavor states are superpositions of neutrino mass eigenstates which evolve as neutrinos propagate. While oscillation experiments have successfully measured the mixing angles and squared mass differences between neutrino mass eigenstates, they remain insensitive to the absolute neutrino mass scale. Therefore, experimental approaches capable of probing the fundamental nature of neutrinos remain one of the central objectives of current particle and nuclear physics searches.

One of the most powerful experimental probes of neutrino properties is the search for $0\nu\beta\beta$. In this hypothetical second-order weak nuclear process, two neutrons simultaneously decay into two protons while emitting two electrons and no antineutrinos. The observation

of such a decay would demonstrate that lepton number is not conserved in weak interactions and that neutrinos are Majorana particles, meaning that they are their own antiparticles [69, 166]. The observation of $0\nu\beta\beta$ would therefore provide a direct indication of physics beyond the SM and potentially offer unique insights into the origin of the neutrino mass.

The study of neutrinos through $0\nu\beta\beta$ is closely related to one of the most profound open questions in physics, which is the observed matter–antimatter asymmetry in the Universe. The matter dominance in the Universe cannot be explained by SM processes alone. Theories such as leptogenesis suggest that Majorana neutrinos in the early Universe could generate an asymmetry in the lepton sector, which is subsequently converted into the baryon asymmetry observed today [2]. Establishing the Majorana nature of neutrinos through the observation of $0\nu\beta\beta$ could provide an avenue to explaining why the observable Universe is dominated by matter.

Detecting $0\nu\beta\beta$ remains extremely challenging. Current half-life limits for $0\nu\beta\beta$ in candidate isotopes exceed 10^{26} years and may extend beyond 10^{28} years depending on the actual neutrino mass scale [55]. Achieving sensitivity to such rare processes requires large quantities of the candidate $\beta\beta$ -decaying isotope, long observation periods, and exceptionally low background levels. Current and next-generation experiments therefore rely on a combination of optimizing detector design, shielding, event topology and reconstruction techniques to suppress background processes that could mimic the signal of interest.

One promising technique to further reduce backgrounds that is possible in LXe experiments is Ba-tagging. In experiments searching for $0\nu\beta\beta$ in ^{136}Xe , the decay produces a ^{136}Ba daughter ion. If the presence of this daughter ion can be directly identified following a potential decay event, it will provide a powerful method for confirming the occurrence of the decay. Since most background processes do not produce ^{136}Ba , the ability to tag ^{136}Ba would provide a nearly background-free identification of $0\nu\beta\beta$ events [6].

The Ba-tagging concept is particularly attractive for large-scale xenon detectors such as the nEXO experiment. In this approach, ions produced in the detector medium are extracted and transported to a region where they can be analyzed and identified using specialized ion manipulation and mass spectrometry techniques.

Several Ba-tagging schemes are currently being developed to enable single-ion identification. One such technique that is discussed here uses a capillary for ion extraction from the LXe detector volume and an RF funnel for subsequent isolation into vacuum. The work presented in this dissertation focuses on the development, commissioning, and integration of several key components required for this Ba-tagging system, particularly the RF funnel and the LPT. Individually, each of these subsystems have been studied previously [116, 121]. However, the successful operation of a Ba-tagging system requires that they operate together as a fully-integrated ion transport and identification chain. The primary goal of the work described here was therefore to commission these subsystems, demonstrate their operation under realistic experimental conditions, and establish the

infrastructure required for future Ba-tagging studies.

8.1 The RF Funnel Subsystem

Previous studies attempted to demonstrate the feasibility of extracting ^{136}Ba ions from GXe using the RF funnel [121, 124]. While the studies were successful at characterizing ion extraction and transport using a ^{252}Cf ion source, no amount of Ba ions could be observed from the extracted ions. These results helped identify several areas of required improvements to enhance performance and detection capabilities. The work presented here involved the re-commissioning of the funnel system and the implementation of two key upgrades aimed at improving ion transport efficiency and operational stability.

RF-Drive Electronics Upgrade

The funnel subsystem, comprising the RF funnel and a SPIG, was operated using a ^{252}Cf source and GAr in order to study ion transport and pressure control. The experimental results obtained during these tests were found to be consistent with previously reported measurements while exhibiting significantly higher ion count rates under similar operating conditions. This improvement in count rate is primarily attributed to the first key upgrade which was the higher operating frequency of 5.75 MHz used in the current RF funnel design compared to previous operations at 2.6 MHz. The maximum measured count rates observed during these studies were approximately two orders of magnitude higher than values reported

in earlier works [124]. However, it should be noted that the current measurements were performed using GAr rather than GXe. Other systematic factors, such as CEM detection efficiency, ion optics alignment, or gas purity could also have contributed to the observed increase. Since the ultimate application of the system involves operation in GXe, further studies will be required to fully benchmark the performance of the funnel under its intended operating conditions. Another interesting observation made during the RF amplitude scans was the increase in ion count rates beginning at RF amplitudes around $100 V_{pp}$. One possible explanation for this behavior is the onset of additional ionization processes involving argon atoms inside the RF funnel. If such ionization processes occur, they could contribute additional ion species to the detected signal. The increase could also be attributed to an increase in transport efficiency of a secondary charged species, resulting in an overall increase in ion count past the previously observed trends. In order to investigate these possibilities and effects, future studies will involve mass measurements of ions extracted from the RF funnel at different RF amplitudes, especially around $100 V_{pp}$. By identifying the mass-to-charge ratios of the detected ions and their relative abundances, it will be possible to determine whether additional ion species are being produced or the increase seen arises from an increase in the overall transport efficiency. Future studies will also benefit from the electronics upgrade suggested in Section 6.2.2, enabling operation beyond the current RF amplitude limit of $125 V_{pp}$ and thereby achieving higher count rates. While the focus of the RF funnel in the context of Ba-tagging is to maximize ion transmission efficiency rather than capacity, ion

transmission studies between the RF funnel and LPT subsystems will greatly benefit from increased ion flux, facilitating tuning and initial testing. Additional improvements to the RF funnel subsystem could also be achieved by applying a DC bias to the funnel electrode stack. The current configuration relies on the SPIG bias potential to define the energy of the transiting ions as seen from Figure 6.10. By floating the RF funnel at a positive potential relative to ground, it may be possible to control the energy of extracted ions more effectively and improve their transmission [167].

Pressure Control System Upgrade

The pressure control capability of the RF funnel subsystem, particularly the pressure outside the RF funnel electrode stack, was improved through the installation of a proportional gate valve (PGV). The PGV provides control over the gas flow between the RF funnel and the cryopump chamber, therefore allowing control over the pressure in the RF funnel chamber. In the current configuration, the valve position is adjusted manually in order to achieve the desired pressure conditions within the RF funnel. While this approach is sufficient for testing the system's response, future operation would benefit from automated control. It is thus recommended to implement a feedback system in the form of proportional-integral-derivative (PID) control. Such a system would allow for the pressure within the funnel chamber to be stabilized automatically in response to changing operating conditions. The necessary provisions for implementing PID control are already in place, with a pressure

gauge installed on the RF funnel vacuum chamber and directly interfaced with the PGV. The PID control must be tested, and its parameters optimized to achieve a faster and more accurate response than is possible with manual control alone. This capability will become particularly important when operating the system with xenon gas, where precise pressure control will be necessary to maintain stable ion transport while enabling gas recovery through the cryopumping system.

8.2 Ion Trapping Studies with the LPT

The LPT subsystem was commissioned as part of this work and was used to demonstrate efficient ion trapping and bunching using a Cs thermal ion source. The LPT subsystem comprises a QMF for filtering background ions and an ICB to cool incoming ions and prepare ion bunches to supply to the MRTOF-MS. The QMF was characterized using the aforementioned stable Cs ion beam, and its MRP was determined to be $m/\Delta m > 100$. The result confirmed that the QMF achieves the minimum required MRP ($m/\Delta m \geq 80$) to filter potential background ions, a key feature required to prevent overloading of the buncher.

One function of the ICB is to receive, collisionally cool, and trap ions for the duration of laser fluorescence spectroscopy, enabling verification of the presence of ^{136}Ba once laser fluorescence capability is added in a future upgrade to the subsystem. The second function of the ICB is to act as a preparatory trap, before sending ions in bunches to the MRTOF-MS

for mass measurements.

Ion Trapping and Bunching in the LPT

Since ions come from the RF funnel as a continuous stream and because ions cannot be accumulated in the buncher as demonstrated in Figure 7.12, incoming ions are first accumulated in the cooler. A few or all of the accumulated ions are subsequently loaded into the buncher periodically where they are further cooled to form an ion bunch with narrow spatial and energy spreads. The ion bunch is then ejected from the buncher and injected into the MRTOF-MS for mass measurements. The results from the commissioning studies detailed in Chapter 7 demonstrated that the LPT is capable of accumulating ions, cooling them through buffer gas interactions, and ejecting well-defined ion bunches suitable for mass analysis. Using tuned values for the buncher potentials and buffer gas pressure combined with TFS in the MRTOF-MS, FWHM values for the ion TOF have been consistently measured in the range of 50–100 ns.

A source of potential ion loss identified during the commissioning process was the resetting of the ICB RF potential. In the current implementation, the resetting process introduces timing variations as shown in Figure 7.4b that can destabilize ions stored in the cooler and lead to ion losses. A potential improvement would involve synchronizing the waveform generator and the FPGA using a global timing reference. Implementing a global clock signal shared between the waveform generator and the FPGA controller would allow for more

precise timing control without requiring the periodic resetting of the RF signal.

Transferring ion bunches from the LPT into the MRTOF-MS required careful tuning of the downstream ion optics. Electrostatic lenses and steerers were used to guide the ions along the beamline and match the spatial acceptance of the MRTOF-MS. Achieving this alignment proved to be one of the challenging aspects of the commissioning process. One of the primary difficulties encountered during this phase of the work was the limited availability of diagnostic tools capable of detecting low intensity ion bunches. To address this challenge, diagnostic upgrades were implemented in the Ba-tagging setup in the form of single-ion capable detectors, as described in Section 5.2. Two CEMs, in particular, were positioned before and after the MRTOF-MS collimating aperture situated at the entrance of the MRTOF-MS in order to tune the transmission of ion bunches. Since the installation of these detectors had to be performed without significantly modifying the existing experimental infrastructure, they were mounted on linear actuators. This allowed for the detectors to be inserted into the ion path during tuning procedures and retracted during normal operation. The addition of these diagnostic detectors proved essential for optimizing the ion transport system. By monitoring the ion signals at multiple locations, it became possible to systematically adjust the electrostatic optics and identify the optimal bias voltages. During this process it was inferred that a small vertical alignment mismatch exists between the beam axes of the LPT and the MRTOF-MS subsystems. The electrostatic steerers, together with the CEMs, can effectively correct the ion bunch

trajectory before arriving at the collimating aperture to ensure good transmission between the LPT and the MRTOF-MS subsystems.

TOF measurements with the MRTOF-MS

Following these upgrades, ion bunches ejected from the LPT were successfully detected at the far end of the MRTOF-MS using CEM4. Subsequent tuning of the MRTOF-MS mirrors allowed the ions to undergo multiple reflections between the electrostatic mirrors, enabling extended storage times and increased mass resolving power.

MRTOF-MS is particularly well suited for applications such as Ba-tagging because it allows for very high resolving power to be achieved within a compact device. By reflecting ions between electrostatic mirrors many times, the effective flight path can be greatly increased without requiring large physical dimensions. Achieving stable operation represents an important milestone in demonstrating the feasibility of the full Ba-tagging concept. The maximum MRP from preliminary TOF measurements was $19\,973 \pm 201$. The current limiting factor to the MRP is primarily the stability and optimization of the mirror electrode potentials. This is because the FWHM of ion bunch TOF measured after TFS was under 100 ns, while the FWHM after 275 isochronous revolutions was ≈ 400 ns. Assuming the FWHM can be maintained under 150 ns for the same number of revolutions, an MRP $> 53\,000$ will be achievable using bunched ions from the LPT. Considering the mass difference ($\Delta m \approx 0.00264$ eV) between $^{136}\text{Ba}^+$ and its primary isobaric background,

$^{136}\text{Xe}^+$, an MRP of $\sim 51\,500$ would allow sufficient separation between the respective mass peaks, while an even higher MRP will be required for clean detection of a single $^{136}\text{Ba}^+$ ion among a much larger population of $^{136}\text{Xe}^+$ ions.

Progress towards achieving higher resolving power with the MRTOF-MS was significantly impacted due to repeated failure of the high-voltage switches used for biasing the MRTOF-MS entrance mirror electrodes. Due to repeated failures, the bias potentials for the mirror electrodes had to be frequently inspected and re-tuned. The MRTOF-MS switches have since been replaced with new high-voltage switches designed to provide improved robustness and greater output stability, specifically addressing this shortcoming. Future TOF measurements are expected to yield better results with a potential of approaching an MRP of $\sim 100\,000$ as was previously suggested through simulation results [168, 169].

Ion Source Development

In addition to the testing of the RF funnel and LPT subsystems, significant progress was made in developing versatile ion sources capable of producing ions across a wide mass range. A test target composed of multiple materials was machined and used in a LAS. Initial experiments using this target demonstrated that a broad range of ion species could be produced. This capability will prove valuable for future studies aimed at characterizing the performance of the LPT and MRTOF-MS across different mass regimes.

While the results presented in this dissertation focus primarily on ions from the Cs

thermal ion source, future studies will extend these investigations to ions produced by laser ablation. LAS-generated ions typically have kinetic energies on the order of 100 eV, which differs from the lower energies expected for ions extracted from the RF funnel subsystem. Additionally, the Cs ion source that has been used for the LPT commissioning provides an ion beam with an energy spread less than 1 eV while LAS output can vary over 50 eV [151]. As a result, additional tuning of the LPT and MRTOF-MS will be required to optimize their performance for these higher-energy ion pulses.

Overall, the work presented in this dissertation represents the first attempt of combining the RF funnel, LPT, and MRTOF-MS subsystems into a unified experimental platform capable of performing ion extraction, manipulation, and identification. While each of these components had been demonstrated individually in previous work, their integration into a single system required extensive commissioning and diagnostic development. Particularly, ion transport from the RF funnel to the LPT has not been achieved yet due to lower ion count of the ions extracted from GAR compared to the ion beam supplied by the Cs ion source. This may require one last detector upgrade to position a CEM directly in front of the QMF in order to tune RF funnel ions to this location. The other, more favorable, option would be the addition of an ion source in the RF funnel subsystem to provide an ion beam of currents in the 100 pA range to enable measurements using a picoammeter and subsequent tuning of electrostatic lenses and steerers.

Future work involving this apparatus will focus on optimizing the system specifically for

Ba-tagging applications. One of the goals will be to measure the overall tagging efficiency of the system, which depends on the combined performance of all subsystems involved in ion extraction, transport, trapping, and identification. Eventually, this system will be coupled to the capillary system and, using the in-LXe ion source discussed in Chapter 3, will enable a demonstration of the complete tagging efficiency of the entire scheme. Determining this efficiency will provide valuable input for evaluating the feasibility of implementing Ba-tagging in a tonne-scale LXe detector.

The successful development of a Ba-tagging system could have significant implications for future searches for $0\nu\beta\beta$. As experiments scale to larger detector volumes in order to achieve sensitivities to half-lives of 10^{28} years or even greater, new background sources begin to dominate. One such background arises from elastic scattering of solar neutrinos, which cannot easily be suppressed through conventional detector design techniques [170]. Since solar neutrino interactions in Xe generally do not produce $^{136}\text{Ba}^+$ ions, the ability to detect the daughter nucleus through Ba-tagging would provide a powerful method for rejecting this otherwise irreducible background. As a result, the successful implementation of Ba-tagging could enable future kilo-tonne-scale experiments to reach even higher sensitivities. The exception to this are neutrino charge-current interactions where, $\nu_e + ^{136}\text{Xe} \rightarrow ^{136}\text{Cs}$ ($T_{1/2} = 13.12$ days) $\rightarrow ^{136}\text{Ba}$ [171]. While the eventual production of ^{136}Ba presents a potential complication for Ba-tagging, the distinct event topology and the relatively long half-life of ^{136}Cs should allow for its effective mitigation.

The commissioning work presented here represents a subsequent step toward realizing this ambitious goal of probing the effective neutrino mass $m_{\beta\beta} < 15 \text{ meV}$. By demonstrating the operation of key subsystems required for ion extraction and identification, this thesis lays the foundation for future studies aimed at achieving reliable and efficient Ba-tagging in xenon-based detectors.

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Appendix A

Supplementary pictures and graphics

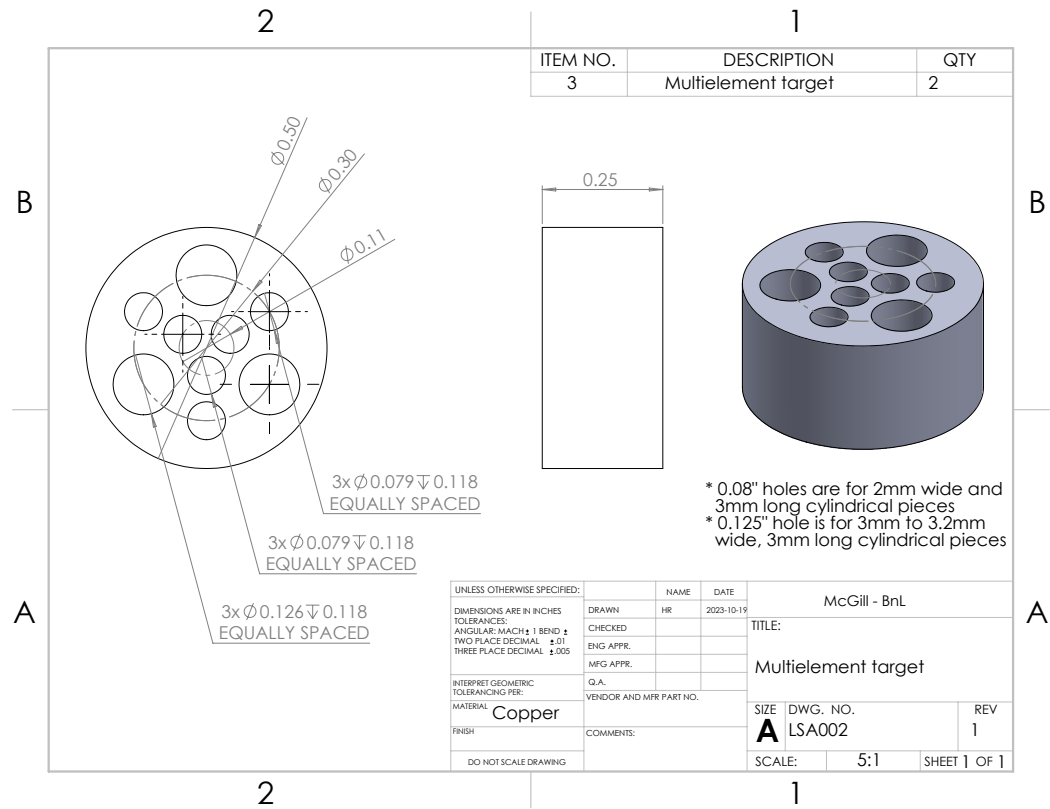


Figure A.1: LAS target drawings.

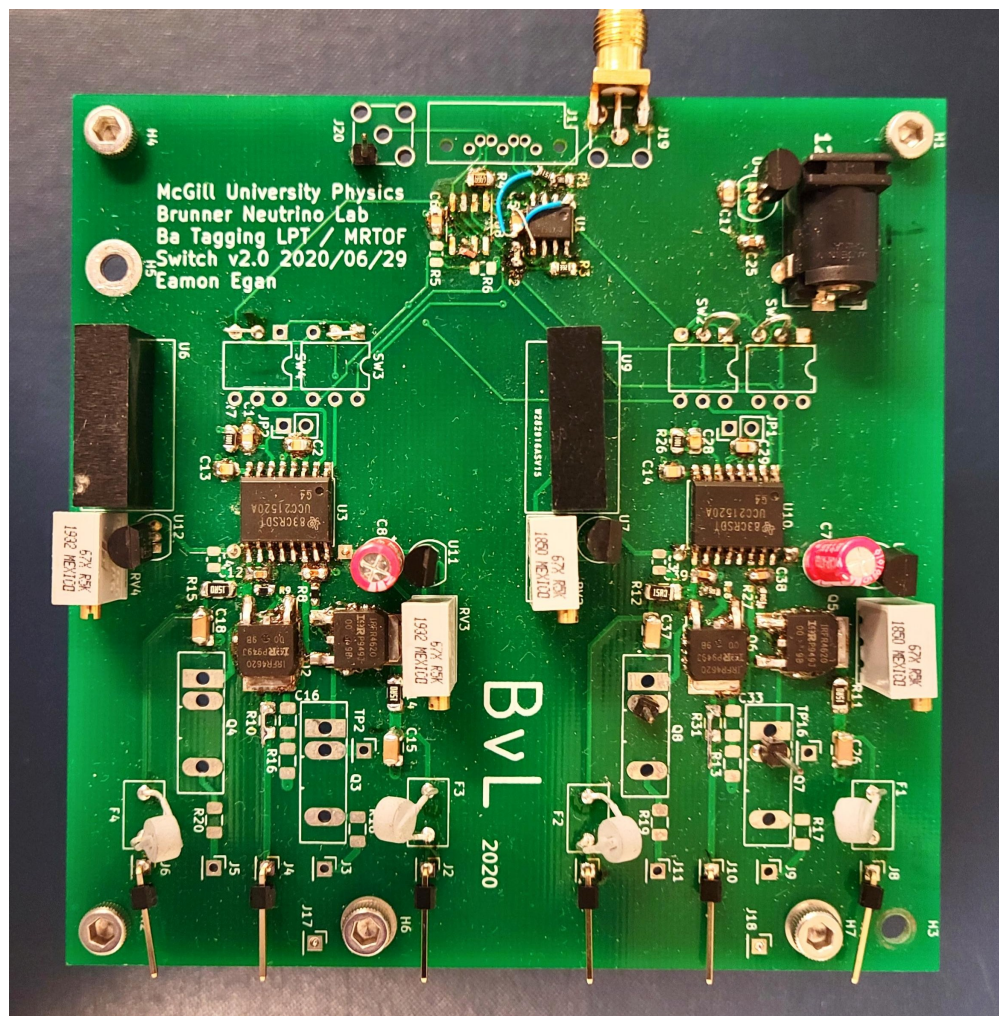
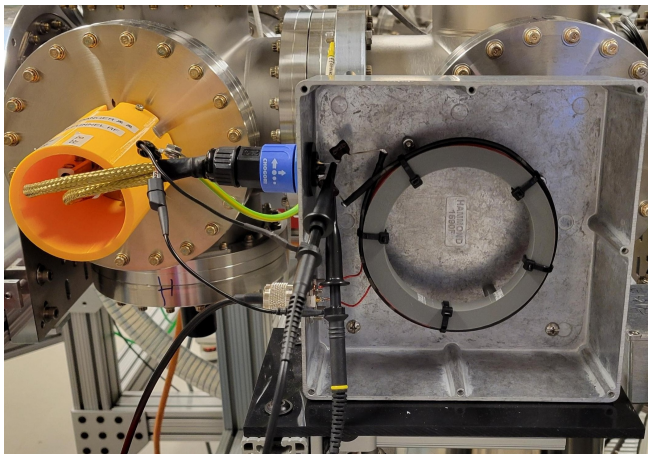
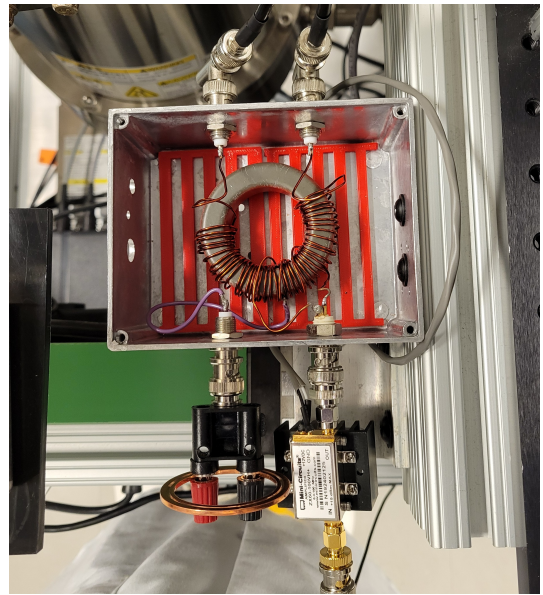


Figure A.2: Voltage switch for fast switching (≈ 50 ns).



(a) RF funnel transformer enclosure. Due to the high power required, an air core is used to couple the primary with the secondary. 2200 pF capacitors are used in series to set the resonant frequency of the circuit to 5.75 MHz.



(b) A center tap on the secondary allows applying a constant DC bias to the SPIG.

Figure A.3: Pictures of transformer enclosures. Amplified sinusoidal signal supplied to the transformer primary is used to supply two out-of-phase sinusoidal signals.

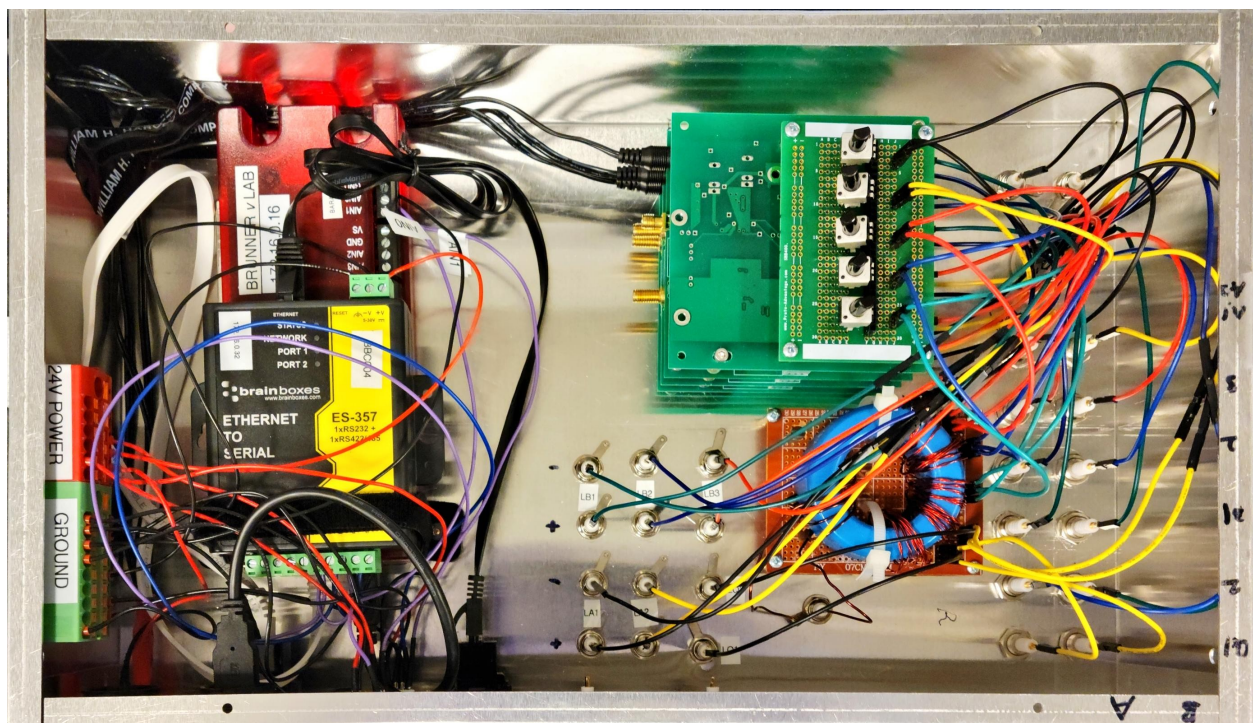


Figure A.4: Electronics box for ICB control.

Appendix B

LPT operation reference values

List of key parameters used in the ion trapping and bunching operation mode of the LPT.

Ion source	10 V	Precooler	-20 V
QMF Segment 1	0 V	Cooler	-20 V
QMF Segment 2	0 V	Cooler tube	-65 V
QMF Segment 3	0 V	Buncher	-25 V

Table B.1: DC biases used for various quadrupole segments involved with ion trapping and bunching operation.

Segment	Frequency (kHz)	Amplitude (V_{pp})
RF funnel	5750	100(1)
SPIG	2300	144(1)
QMF	750	68.0(3)
ICB	1000	156(2)

Table B.2: RF parameters used various segments in the Ba-tagging system.

Appendix C

RF amplitude measurements system

Summary of the RF response of the system for various values of input RF amplitude while operating at the respective operating frequencies. The input from the waveform generator is supplied to RF amplifiers, followed by the transformer produce the two RF phases that are then supplied to the electrodes. The amplitudes presented here were measured using a high impedance probe at the electrical feedthroughs leading into the vacuum chamber to the respective electrodes.

RF in (V)	RF out a (V_{pp})	RF out b (V_{pp})
0	0	0
0.05	17.29 ± 0.17	15.35 ± 0.21
0.10	33.14 ± 0.28	28.95 ± 0.38
0.15	49.96 ± 0.50	39.75 ± 0.55
0.20	70.1 ± 0.5	65.4 ± 0.7
0.25	91.6 ± 0.8	86.9 ± 0.8

Table C.1: RF amplitude measurements for the RF funnel (RF frequency - 5.75 MHz).

WFM setting	Oscilloscope reading (V_{pp})	Std (V)	DC offset (V)
0.010	6.70	0.020	+0.038
0.050	32.29	0.036	+0.024
0.075	46.91	0.053	+0.300
0.100	62.06	0.079	+0.173
0.200	115.62	0.128	+0.740
0.300	163.54	0.197	+1.080

Notes: DC offset present and generally increases with amplitude.

Table C.2: RF output in **QMF**, measured at QQ2a using an SHV T on the QMF box and a 10:1 probe (RF frequency - 750 kHz).

WFM setting	Oscilloscope reading (V_{pp})	Std (V)	DC offset (V)
0.01	2.269	0.016	+0.07
0.05	11.389	0.026	+0.15
0.10	22.858	0.053	+0.25
0.20	45.050	0.055	+0.18
0.25	56.446	0.120	-0.30
0.30	66.731	0.120	-0.95
0.40	88.444	0.120	-1.65
0.50	112.290	0.166	-2.35
0.60	131.790	0.164	-3.00

Notes: DC offset appears to scale with amplitude (~ -3 V at WFM0.60 / 131 V_{pp}); both phases balanced.

Table C.3: RF output in **precooler**, measured at LQ1a using an SHV T and a 10:1 probe (RF frequency - 1 MHz).

WFM setting	Oscilloscope reading (V_{pp})	Std (V)	DC offset (V)
0.01	2.233	0.016	+0.055
0.05	11.711	0.026	+0.105
0.10	23.450	0.034	+0.213
0.20	47.017	0.055	+0.356
0.30	69.700	0.095	+0.270
0.40	93.037	0.117	+0.540
0.50	115.840	0.106	+0.650
0.60	138.640	0.170	+0.980

Notes: DC offset scales with amplitude; phases not equally balanced; LQ2a is higher than LQ2b by $\sim 3\text{--}5\text{ V}$; offset depends on CH601 (DC bias) state. A conservative uncertainty of 2.5 V on the RF potential is reasonable.

Table C.4: RF output in **cooler**, measured at LQ2a using the selector switch on the LPT box and a 10:1 probe (RF frequency - 1 MHz).