Contamination Study for the PI-LIST Ion Source

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1 Abstract

This project aims to improve the production and precision of isotopically enriched radioactive ion beams using advanced laser ionization techniques. Resonance Ionization Laser Ion Sources (RILIS) are employed at CERN-ISOLDE for their high selectivity and efficiency. The Laser Ion Source and Trap (LIST) enhances beam purity by spatially separating the laser ionization region from the hot atomization cavity, reducing isobaric contamination. The Perpendicularly Illuminated Laser Ion Source and Trap (PI-LIST) addresses Doppler broadening by creating a crossed laser and atom beam environment, achieving sub-Doppler resolution of 100-200 MHz. Despite these advancements, francium contamination due to its low ionization potential remains a challenge. To mitigate this, COMSOL simulations are conducted to explore solutions such as repeller coatings, improved thermal insulation, and materials with lower work functions.

2 Introduction

The study of radioactive ion beams (RIBs) is crucial for exploring the fundamental properties of atomic nuclei, such as spin, magnetic and electric moments, and changes in mean-squared charge radii. Resonance Ionization Laser Ion Sources (RILIS) [1] are widely used at facilities like CERN-ISOLDE [2] due to their high selectivity and efficiency in producing isotopically enriched RIBs. By employing wavelength-tunable lasers, RILIS selectively ionizes specific electronic shell transitions, allowing for the precise targeting of desired elements while minimizing contamination from unwanted species.

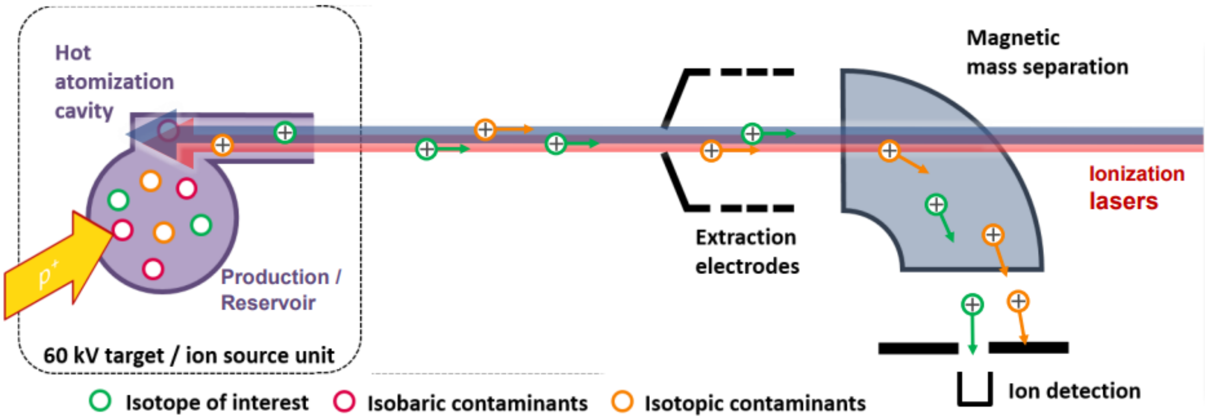

Figure 1: Surface plot of electric potential in the ion source setup.

To further enhance beam purity, the Laser Ion Source and Trap (LIST) was developed in collaboration with Johannes Gutenberg University. LIST improves upon the traditional RILIS method by spatially separating the laser ionization region from the hot atomization cavity, significantly reducing isobaric contamination.

3 PI-LIST Experiment Setup

The Perpendicularly Illuminated Laser Ion Source and Trap (PI-LIST) was introduced to overcome this challenge by integrating a crossed laser and atom beam configuration, effectively targeting and minimizing lateral velocity classes. This novel approach achieves sub-Doppler resolution, significantly enhancing the precision of nuclear structure studies. Successfully integrated at ISOLDE in 2022 [?], PI-LIST demonstrated an impressive improvement in resolution, achieving 100–200 MHz compared to the GHz-scale broadening seen in conventional setups. Figure 2 shows the experimental setup of the PI-LIST, depicting the crossed laser and atom beam environment that enables sub-Doppler resolution.

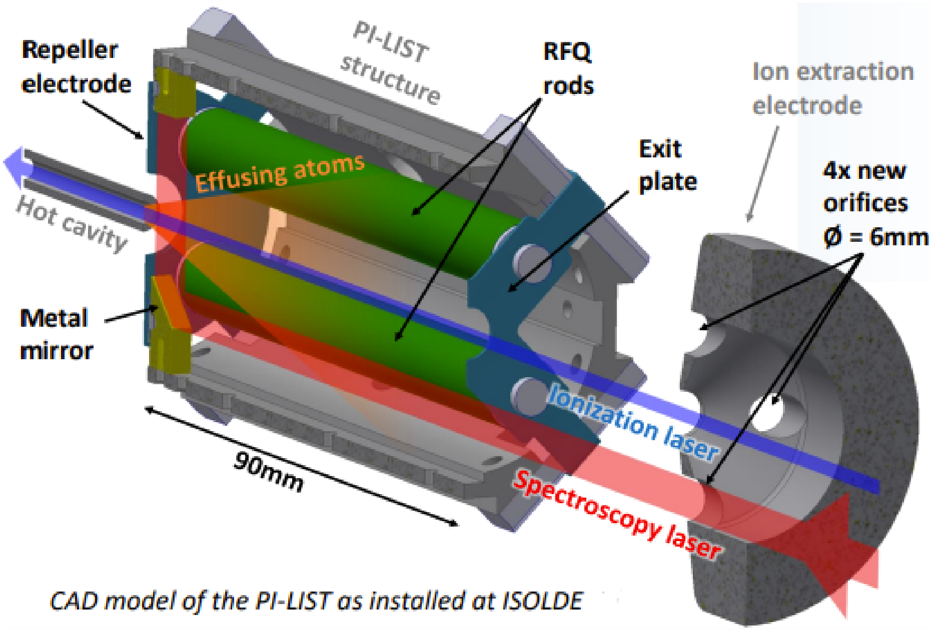

Figure 2: CAD model of the PI-LIST as installed at ISOLDE.

Despite a lower efficiency of approximately 0.01% compared to the 10% of standard RILIS, PI-LIST's ability to achieve sub-Doppler resolution has greatly benefited research within the EU network LISA (Laser Ionization and Spectroscopy of Actinides), enabling detailed investigations of neutron-rich actinium and other complex nuclear phenomena.

4 Experimental Results

During the initial LIST campaigns [Fink2013, Fink2015] and the 2022 PI-LIST experiment, substantial amounts of francium were detected despite employing suppression modes for non-laser ions [**?**]. Figure 3 provides data from these experiments, illustrating the unexpected presence of francium ions, which pose a significant contamination challenge. The unexpected presence of francium, which has a low ionization potential (IP = 4.1 eV), suggests surface ionization at the repeller due to insufficient thermal insulation, particularly given its proximity to the hot cavity. This contamination study focuses on understanding and mitigating unintended ionization processes in the PI-LIST setup to refine its performance in nuclear physics research further.

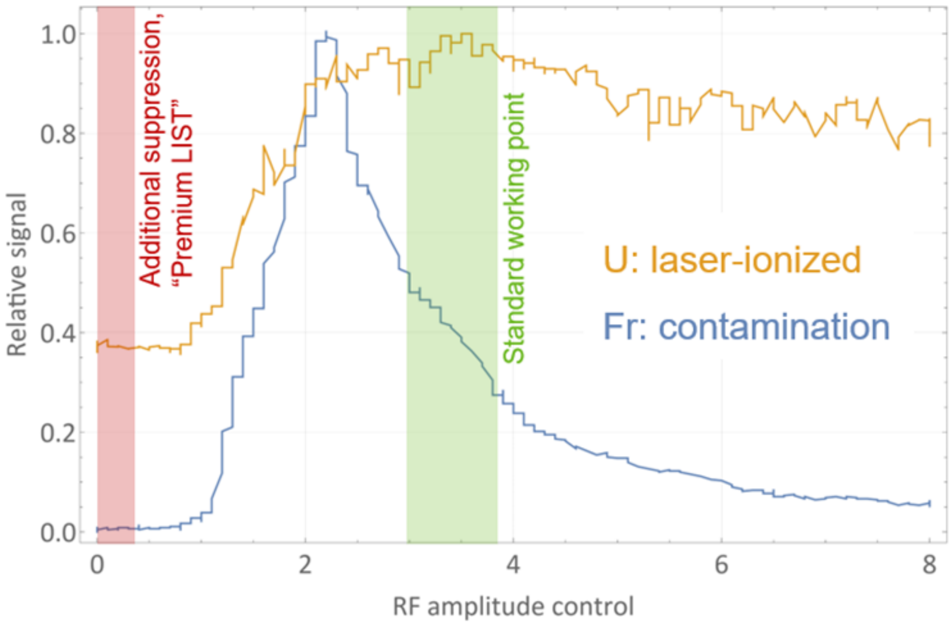

Figure 3: Dependence of laser-ionized (U) and non-laser related contamination (Fr) on the RFQ voltage amplitude in LIST mode.

5 COMSOL Simulation

To address the contamination issue, detailed simulations were conducted using COMSOL Multiphysics. These simulations focused on analyzing the electric potential distribution and evaluating thermal effects within the ion source. The objective was to optimize the system by minimizing contamination risk and enhancing ion extraction efficiency.

5.1 Simulation Setup

1. **Mesh Configuration:** A high-resolution finite element mesh with a maximum element size of 0.001 m was created to capture critical physical behaviors. Key regions of interest included areas with high electric field gradients and thermal loadings around the PI-LIST ion source. Boundary layers were added to ensure accurate modeling of electric and thermal effects in these zones, facilitating a balance between computational efficiency and result precision.

2. **Thermal Effects:** The simulation accounted for the thermal conductivity of primary materials, including stainless steel and ceramic insulators, to evaluate the impact of temperature gradients on contamination. Heat sources from resistive and laser-induced heating were included to replicate realistic operational conditions, with specific boundary conditions to model insulation and thermal expansion effects. This analysis helps in identifying optimal materials and insulation strategies to limit temperature-induced contamination.

3. **Electrostatic Potential:** The electric potential distribution was modeled to explore how different repeller configurations influence contamination. By testing various geometries and materials with different work functions (such as tungsten and molybdenum), the simulation aimed to reduce unwanted ionization of contaminants like francium. This approach provided insights into repeller designs that can enhance ion purity by limiting undesired electric field effects at specific locations.

The combined insights from these simulations provide a foundational basis for minimizing contamination in the PI-LIST setup. Further refinements in future simulations will help validate and enhance the proposed configurations.

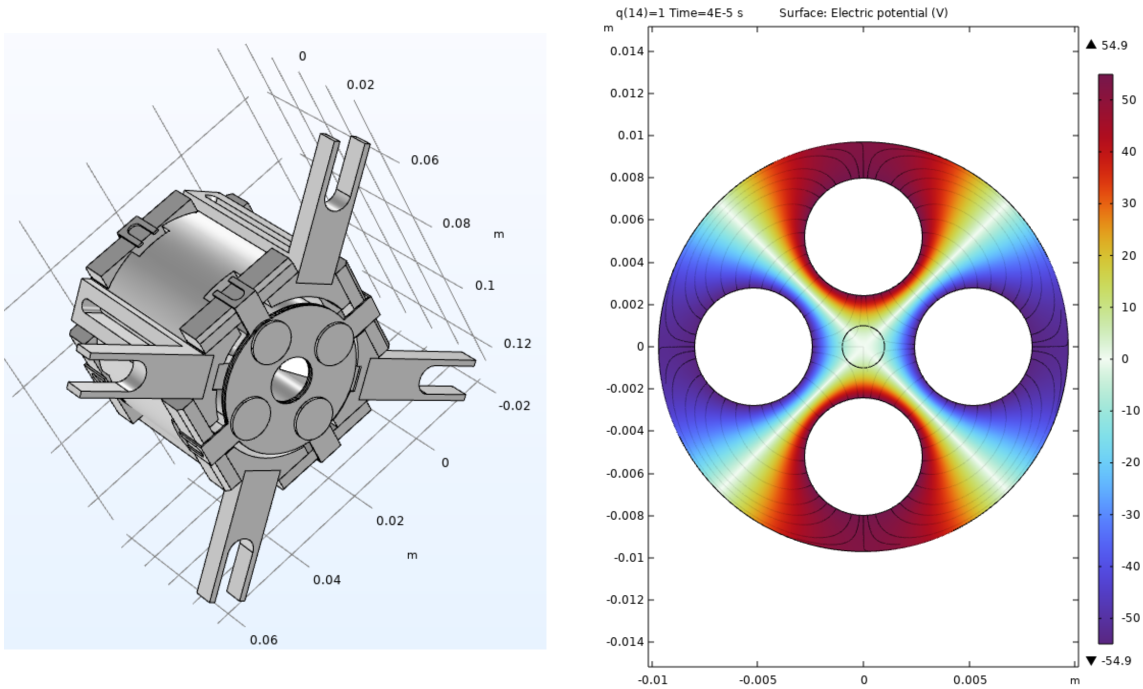

Figure 4: COMSOL simulation showing part geometry (left) and the distribution of electric potential (right). The results guide contamination mitigation by identifying regions with concentrated electric potential and thermal hotspots.

These simulations enable us to identify key areas where contamination is most likely to occur, allowing for targeted adjustments to the ion source design to mitigate risks.

6 Results

The results obtained from the COMSOL simulation demonstrate a notable reduction in error across both electrostatic and thermal parameters over the course of iterative calculations. As shown in Fig. 5, the error decreases logarithmically over 150 iterations, starting from an initial value of 10^2 and reaching below 10^{-3}. This trend indicates a consistent improvement in accuracy, though the convergence rate slows during later stages, suggesting that additional refinement may be required to achieve optimal results more efficiently.

Further analysis in Fig. 6 shows that the error in the electrostatic parameter converges rapidly, reaching near-zero values (10^{-16}) within a few iterations. This confirms the robustness of the approach for handling electrostatic aspects in the system. However, the temperature parameter exhibits residual errors, remaining around 10^{-2}, likely due to minor instabilities or thermal effects that have yet to be fully accounted for in the current simulation setup. Addressing these residuals in future simulations will be essential to further enhance the overall precision of the model.

7 Conclusion and Future Work

These simulations provide a preliminary evaluation of different approaches to mitigating francium contamination, which are crucial for enhancing the precision of our measurements. Although exact results are still pending, the ongoing analysis aims to identify optimal solutions involving material selection and thermal management strategies.

In the preliminary results, the Conjugate Gradient and Segregated Solver methods demonstrated distinct advantages in reducing error rates. The Conjugate Gradient method effectively decreased error over multiple iterations, though it displayed a decelerating convergence at later stages, indicating room for potential improvement. The Segregated Solver showed rapid convergence for electrostatic parameters, achieving nearly zero error within a few iterations, while the temperature parameter presented residual errors, suggesting further optimization is needed to address thermal effects.

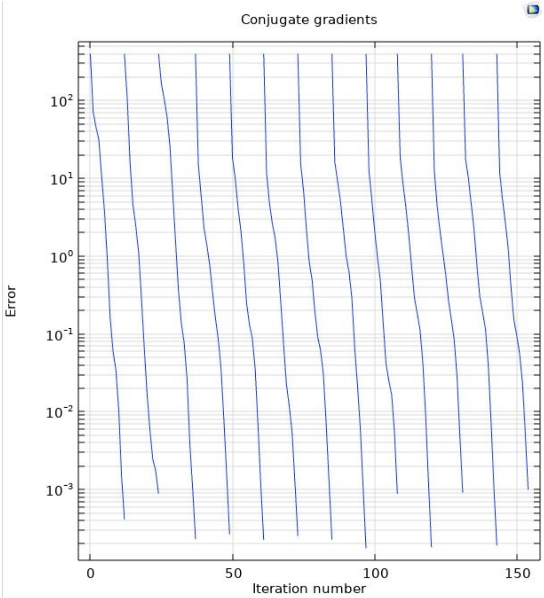

Figure 5: Error reduction over 150 iterations.

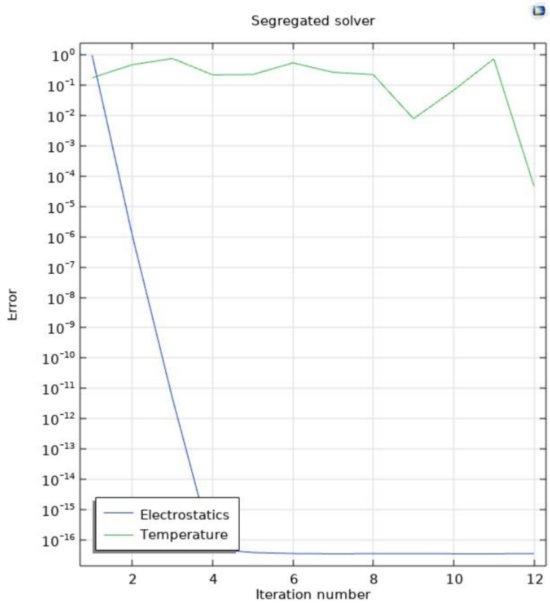

Figure 6: Error convergence for electrostatic and thermal parameters.

Future work will focus on refining these simulations, validating the approaches experimentally, and exploring additional modifications to further minimize contamination. Collaborative efforts are planned to enhance simulation accuracy, improve material configurations, and test alternative solver techniques. Our continued efforts are expected to significantly reduce francium contamination and improve the overall accuracy of our experimental measurements once the results are fully realized.improve the overall accuracy of our experimental measurements once the results are fully realized.

8 Acknowledgement

Spending the summer working on this project has been an incredibly rewarding and fulfilling experience, made possible by the support of many dedicated individuals. I am deeply grateful to my supervisor, Asar AH Jaradat, for her unwavering guidance, her patience in answering my numerous questions, and her invaluable assistance in developing simulations. Her encouragement and expertise were instrumental in helping me make significant progress, and I am truly thankful for her mentorship. I would also like to thank Reinhard Heinke, whose support and positivity consistently brightened my days.

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I also wish to thank my fellow summer participants for their camaraderie and support throughout this journey. I look forward to continuing my work and building upon this invaluable experience in the future.

References

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