ML-TUNE: Machine Learning-Guided Tuning for Efficient Accelerator and Experiment Setup, Sabrina Appel, GSI

1. Research objectives

In the coming years, the commissioning of the FAIR accelerator complex will mark a milestone in high-intensity nuclear physics. Originally designed before the widespread adoption of AI technologies, the FAIR infrastructure offers unique potential for the integration of ML-guided automation in both accelerator operation and experimental workflows. Reducing accelerator and experiment setup time has a direct and significant **impact on the efficiency** with which experiments can begin **collecting data**, thereby increasing overall scientific output.

Our primary objective is to investigate and develop machine learning methods to:

- Significantly reduce the setup and tuning time of the Super-FRS,
- Maintain or improve beam quality and transmission,
- Enhance and accelerate the isotope identification process through online data analysis,
- Enable adaptive, model-based calibration of detectors and time-of-flight systems.

Ongoing R&D addresses several of these aspects. A current project develops a higher-order ion-optical model of the Super-FRS, based on field maps and magnet data, which forms the basis for advanced multi-fidelity optimization **combining fast simulations with online measurements**. Initial results at synchrotron SIS18 are encouraging and could be extended to the Super-FRS as part of a digital twin framework.

ML methods could also support improved isotope identification. Systematic assignment shifts due to calibration errors or detector drift can be detected by trained ML models. The open-source Geoff framework[1], developed and maintained by GSI and CERN, facilitates such workflows through standardized integration of classification models and automated cross-correlation. This reduces ambiguity, improves speed and robustness, and **ensures reliable data collection**.

Our approach integrates physics-informed simulation, historical experimental data, and modern control algorithms such as reinforcement learning, Bayesian optimization, and classification models. Geoff supports a modular, standardized approach to accelerator optimization using RL methods and Gymnasium APIs. The ultimate goal is to establish a transferable framework for ML-guided setup and decision-making in complex experimental environments, with the Super-FRS serving as a reference case.

2. Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)

This project aligns directly with the goals of Transnational Access infrastructures by contributing to improved accessibility and usability of large-scale research facilities through

[1] P. Madysa, S. Appel, V. Kain and M. Schenk: Geoff: The Generic Optimization Framework & Frontend for Particle Accelerator Controls, https://arxiv.org/abs/2506.03796

intelligent automation. Specifically, the Super-FRS at FAIR (GSI) will serve as a pilot platform for ML-driven optimization and experimental guidance.

Furthermore, the use of **Geoff** and related machine learning tools has the potential to support **Virtual Access** by enabling remote configuration. However, the actual implementation of such remote access capabilities depends on site-specific safety and security regulations. Remote access to accelerator control systems is only feasible if explicitly permitted by the hosting research institution. In this context, solutions such as the **Role Based Access Control (RBAC)** system used at CERN provide a secure and standardized interface for enabling supervised, restricted, and auditable remote operations. Notably, the **Geoff framework — an open-source project supported by Euro-Labs (Grant Agreement no. 101057511)— already supports integration with RBAC**, facilitating safe and controlled remote access for ML-driven accelerator optimization and experiment preparation. This could allow users not only to monitor and guide the optimization process remotely, but also to dynamically redefine optimization goals based on evolving experimental needs. Geoff facilitates hands-on training for users without prior experience in beamline tuning, based on simulation and online interaction.

The results of this project, including tools and interfaces, will contribute to the broader community through open-source dissemination, and can serve as a model for Virtual Access strategies at other facilities.

3. Estimated budget request

We request funding for one full-time PhD position (E13, TVöD scale) for a period of three years. The work will focus on a selected aspect of the proposal, depending on the overall scope and complementarity within the consortium. GSI has already initiated work on related topics—such as ion-optical modeling, ML-based online optimization at synchrotron and existing FRS, and the development of the Geoff framework—on which the PhD project will build. An annual travel budget of €4,000 is foreseen to support collaboration meetings and conferences.

All necessary infrastructure and materials (e.g., office space, beam time, computing resources) will be provided by GSI. Including institutional overhead at a factor of 1.27, the total estimated budget request amounts to approximately **€300,000**.

4. Participating and partner institutions

- GSI Helmholtz Centre for Heavy Ion Research (Germany)

- Technical University of Darmstadt – Control and Cyber-Physical Systems Group

- CERN (Switzerland) – contributor to shared framework development (Geoff)