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DEVELOPMENT OF AN ACTIVE BEAM-STABILIZATION SYSTEM FOR ELECTROFISSION EXPERIMENTS AT S-DALINAC*

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Abstract

The r-process fission cycle terminates the natural synthesis of heavy elements in binary neutron-star mergers. Fission processes of transuranium nuclides will be studied in electrofission reactions at the S-DALINAC. Due to the minuscule fissile target, the experimental setup requires an active electron-beam-stabilization system with high accuracy and a beam position resolution in the submillimeter range. In this contribution, requirements and concepts for this system regarding beam diagnostics elements, feedback control and readout electronics are presented. The usage of a beam position monitor cavity and optical transition radiation targets to monitor the required beam parameters will be discussed in detail. Additionally, various measurements performed at the S-DALINAC to assess requirements and limits for the beam-stabilization system will be presented. Finally, the option to use advanced machine learning methods, such as neural networks and agent-based reinforcement learning, will be discussed.

INTRODUCTION

The superconducting Darmstadt linear electron accelerator (S-DALINAC) at the institute for nuclear physics at the Technische Universität Darmstadt is used for scientific research in nuclear spectroscopy and meteorology, nuclear astrophysics and accelerator science [1] and can be operated in energy-recovery modes [2, 3]. The current layout of the S-DALINAC is shown in Fig. 1. Due to its superconducting design the accelerator is able to provide a continuous-wave electron beam at a frequency of 2.997 GHz with a kinetic design energy of up to 130 MeV. The beam quality can be further improved using the scraper systems located in both the low and high energy sections to reach its minimum design energy spread of 10^{-4} with bunch lengths of smaller than 2 ps [4]. The electron beam can be utilized at various experimental setups including the QCLAM magnet spectrometer. Multiple high-resolution (e,e') and (e,e'γ) coincidence experiments have been conducted successfully at the QCLAM [5, 6].

Within the cluster project ELEMENTS a new series of measurements based on electron-induced fission at S-DALINAC is proposed to aim at a better understanding of the natural synthesis of heavy elements in our universe. While the details of the proposed experiment are provided in the following chapter, the requirements for the accelerator facility are challenging due to the miniscule radioactive target of 1 mm, the request of ultra-short bunch lengths in the order of 1 ps and the demand for stable beam conditions for several hundreds of hours of measurement. In particular, the monitoring and control of the beam spot size and position are of importance.

Therefore, a new active beam-stabilization system is being designed for electrofission experiments at the QCLAM spectrometer at the S-DALINAC. This project includes the commissioning of beam diagnostics elements and correction magnets including an in-house developed beam position and phase monitor. Additionally, the electronics layout for signal readout and processing will be designed. The focus is on utilizing existing in-house developed electronics and commercially available solutions. As feedback control algorithm both the performance of traditional PID (Proportional–integral–derivative) controllers and machine learning methods will be assessed. To test and optimize the control mechanism beforehand, the creation of a virtual test environment based on neural networks and beam dynamics simulations are planned.

ELECTROFISSION AT S-DALINAC

In order to investigate fission reactions of actinides and their dependence of the excitation energy of the nucleus, electron-induced fission will be employed at the S-DALINAC. It allows the determination of the excitation energy of the actinide target nucleus. Additionally, higher multipoles can be excited and studied.

A schematic representation of the proposed electrofission setup is shown in Fig. 2. The electron beam will be delivered by S-DALINAC with a beam current of 3 µA, electron energies of the order of 100 MeV and a 3σ beam spot size smaller than 1 mm at the electrofission interaction point. The electrofission target has a diameter of 1 mm and a target thickness of approximately 350 $\mu g/cm^2$. After its interaction with an electron the target nuclei can decay via fission. An accurate description of this process, which is not available up to date, requires the measurement of both fission fragments in coincidence. While e.g. photon-induced fission primarily excites E1 transitions, in electrofission higher multipole orders such as E2 and E3 can be exited. As electron scattering experiments allow the decoupling of excitation energy and momentum transfer, a model-independent multipole decomposition using the electrofission cross section [7]

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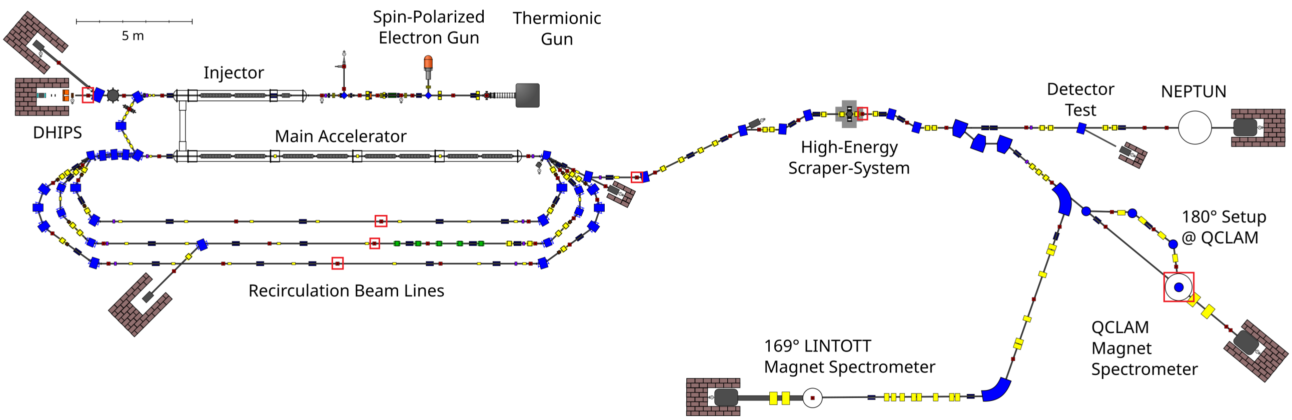

Figure 1: Floorplan of the S-DALINAC. The electrofission experiment as well as the beam stabilization system will be set up at the QCLAM spectrometer. The OTR setups marked in red will be upgraded with fast cameras to allow high-precision beam stability measurements.

$$\frac{d^2\sigma_f}{d\omega\, d\Omega_e} = \sigma_M \sum_{\lambda=0}^{\infty} P_f(E\lambda,\omega)|F(E\lambda,q,\omega)|\frac{dB}{d\omega}(E\lambda,\omega)$$

is possible. Here, ω is the excitation energy, Ω_e the solid angle of the spectrometer, σ_M the Mott cross section, λ the multipole order, P_f the fission probability, F the form factor and B the strength function. Due to its relatively low cross section, measurement periods in the order of several hundreds of hours are planned.

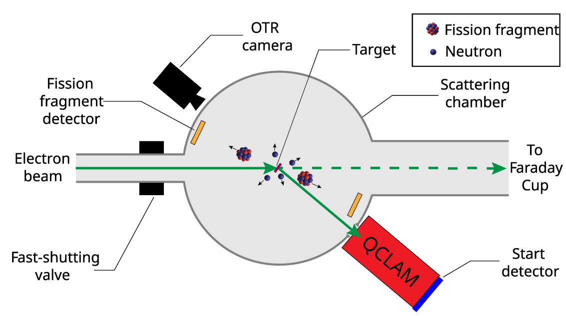

Figure 2: Schematic overview of the electrofission setup design. After interacting with an electron the target nucleus decays via fission. Both fission fragments are detected in coincidence with double sided silicon strip detectors.

DESIGN OF THE BEAM STABILIZATION SYSTEM

The proposed electrofission experiment demands a high control and stability of beam parameters over a large measurement period. As the long-term stability of the beam position and size has not been studied at the S-DALINAC, several existing OTR (optical transition radiation) screen stations (see Fig. 1) are upgraded by ultra-fast cameras that can reach 300-600 fps (frames per second). Within the upcoming beamtime the beam stability and frequency of distortions, and therefore the required frequency of the beam stabilization system, is examined. The desired position resolution and mean stability of the stabilization system is aimed to be smaller than 500 µm. The design layout of the active beam stabilization system is outlined in Fig. 3.

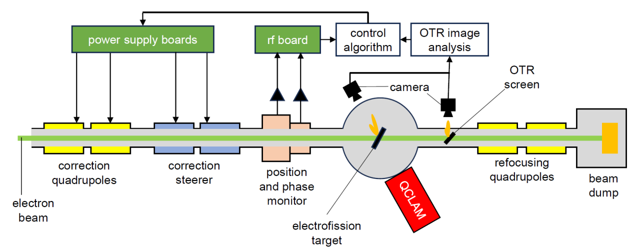

Figure 3: Sketch of the beam stabilisation system. OTR light emitted by both the electrofission target and OTR target is evaluated to determine the beam profile. Additionally, a non-destructive beam position measurement is deducted with a resonator cavity. The signal will be processed by the control algorithm to adjust the correction magnet currents.

Beam Diagnostics

To receive a transverse center beam position signal for beam spots of smaller than 500 µm two methods are proposed and pursued in parallel. As preferred method the observation of OTR directly emitted at the electrofission target is proposed. Transition radiation is emitted when a relativistic charged particle crosses the boundary between two media with different permittivity as the electric field has to rearrange at the boundary [8]. The radiated power for an electron with Lorentz factor $\gamma \gg 1$ can be described by [9]

$$W_o(\theta) = \frac{e^2}{4\pi^3\epsilon_0 c}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}$$

with $W_o = d^2W/d\omega d\Omega$ the spectral energy distribution and $\beta = v/c$ the electron velocity. Additionally, the total transmitted intensity is proportional to γ and the plasma frequency of the target material. The emitted OTR light can be observed with a fast camera. The analysis of the target image gives access to the beam profile parameters right at

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the electrofission interaction point. Here, the resolution and frequency of the transverse beam profile signal is only dependent on the OTR intensity and camera resolution and frame rate as the OTR is emitted instantaneously and no broadening effects occur. A beam position resolution of $\ll$ 100 μm at a frequency of 35 Hz has been measured at OTR setups at the S-DALINAC [10]. The observation of OTR at the target material has been used before to improve the experimental analysis at the QCLAM [11].

Depending on the target material and the QCLAM interaction chamber geometry it cannot be guarantied that OTR at the electrofission target is accessible. Therefore, an alternative method is pursued in parallel. The beam will be monitored non-destructively with an in-house developed cavity beam position monitor shortly before the interaction chamber [12]. As the cavity beam position monitor is currently decommissioned, a first test of its performance has been conducted (see Fig. 4). With the existing electronics beam positions with an increment of 1 mm could be resolved at a beam current of 500 nA. In order to derive the beam position at the interaction point, an OTR screen will be installed behind the electrofission target and the emitted OTR light will be evaluated as in option 1. A position resolution of 100 μm of the cavity beam position monitor has been shown for beam currents of 1 μA [12]. The resulting position resolution at the interaction point will be examined within the commissioning phase.

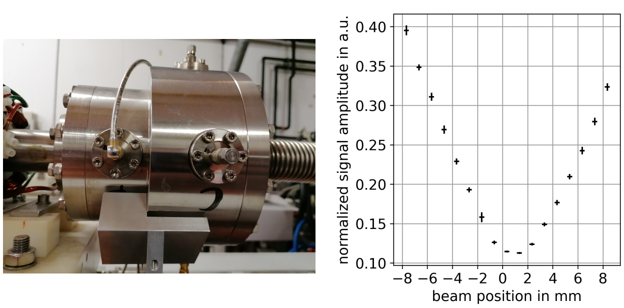

Figure 4: Left: Image of an in-house developed cavity beam position monitor for non-destructive phase and beam position measurements. Right: Test of a decommissioned cavity beam position monitor with existing readout electronics at a beam current of 500 nA. Beam positions with an increment of 1 mm can be resolved.

Readout Electronics

The choice of readout electronics depends strongly on the required repetition rate of the beam stabilization system. The OTR cameras will be chosen to have the maximum resolution for the given system repetition rate.

For the cavity beam position monitor, the extracted signal power is $P \propto x^2 I^2$ where x is the transverse beam shift and I is the beam intensity. To be sensitive to $x < 1$ mm for beam currents of 100 nA to 2 μA while protecting the following electronics of large P induced by $x \gg 1$ mm in the beam tuning process, the existing amplification electronics will be substituted with state-of-the-art low-noise amplifiers and an adjustable attenuation. For the signal processing of the amplified 2.997 GHz signal, in-house developed rf boards are available. They consist of an IQ (In-phase and quadrature) demodulator, an amplitude detector and a FPGA (Field Programmable Gate Array). The transverse center beam position is calculated directly from the IQ vector on the FPGA.

The power control boards of the correction steerers are in-house developed power supplies with an input signal processing of up to 7 Hz. If a faster signal processing is required, new power control boards have to be acquired. The hardware implementing the control algorithm depends on the control cycle repetition rate. The EPICS-based control system (Experimental Physics and Industrial Control System) allows scanning frequencies of up to 10 Hz [13, 14]. For higher frequencies FPGA boards with implemented control algorithm configurations can be used.

Feedback Control

A first test of a feedback control using a Python-based PID controller with EPICS interface has been conducted. A steerer has been used to manipulate the beam position while a second correction steerer was controlled to stabilize the beam to a fixed position on a downstream beryllium oxide screen. Both steerer magnets were operated with a frequency of 5 Hz. The horizontal center beam position was calculated by Gaussian fits on the vertically projected image profile. As shown in Fig. 5 the correction steerer was able to stabilize the beam within a 2σ-interval of 0.84 mm. Yet, beryllium oxide has broadening effects and the strong distortion of the beam most likely does not model the noise of the S-DALINAC electron beam sufficiently. A beam stabilization test measurement using an OTR target is scheduled for the upcoming beamtime where a higher beam stability is expected.

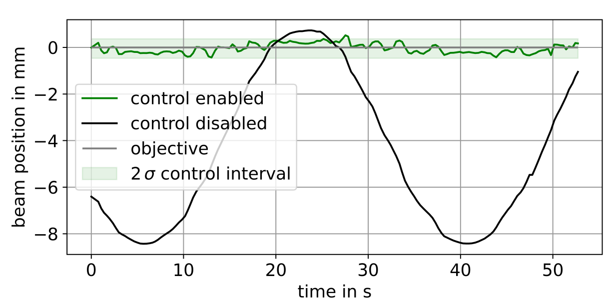

Figure 5: First test of a beam stabilization with a PID controller and implemented fast target analysis algorithm. Despite the strong simulated distortion, the correction magnet was able to keep the center beam position within a 2σ-interval of 0.84 mm.

As surrogate models of accelerator subsystems have been proven useful in analyzing and refining the underlying system, it is planned to create such a system based on both

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simulations and machine learning techniques like neural networks or polynomial chaos [15]. The constructed surrogate models will serve as training and testing environments for different control algorithms, such as PID controllers and supervised learning agents.

CONCLUSION

The S-DALINAC is well suited to provide a high-quality electron beam for the upcoming electrofission experiments. Yet, due to its challenging requirements including a beam spot size of 1 mm and a position stability of 500 µm, an active beam stabilization system is essential for the success of the electrofission project. Multiple OTR setups are currently being upgraded to allow a systematic investigation of the beam stability within the upcoming beamtime. The presented design of the stabilization utilizes existing in-house knowledge while remaining flexible to match the electrofission setup requirements.

REFERENCES

[1] N. Pietralla, "The Institute of Nuclear Physics at the TU Darmstadt", *Nucl. Phys. News*, vol. 28, no. 2, pp. 4–11, 2018. doi:10.1080/10619127.2018.1463013

[2] M. Arnold *et al.*, "First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac", *Phys. Rev. Accel. Beams*, vol. 23, p. 020101, 2020. doi:10.1103/PhysRevAccelBeams.23.020101

[3] F. Schliessmann *et al.*, "Realization of a multi-turn energy recovery accelerator", Nat. Phys., vol. 19, pp. 597–602, 2023. doi:10.1038/s41567-022-01856-w

[4] F. Hug, "Erhöhung der Energieschärfe des Elektronenstrahls am S-DALINAC durch nicht-isochrones Rezirkulieren", Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2013. https://tuprints.ulb.tu-darmstadt.de/id/eprint/3469

[5] G. Steinhilber, "The electron-gamma coincidence set-up at the S-DALINAC" , Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2023. doi:10.26083/tuprints-00022993

[6] C. Lüttge *et al.*, "Large-aperture system for high-resolution electron scattering", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 366, no. 2-3, pp. 325–331, 1995. doi:10.1016/0168-9002(95)00497-1

[7] F. Zamani-Noor and D. S. Onley, "Virtual photon theory in electrofission", *Phys. Rev. C*, vol. 33, no. 4, pp. 1354–1366, 1986. doi:10.1103/PhysRevC.33.1354

[8] V. L. Ginzburg and I. M. Frank, "Radiation of a uniformly moving electron crossing a boundary between two media", *JETP*, vol. 16, p. 15, 1946.

[9] V. L. Ginzburg and V. N. Tsytovich, "Several problems of the theory of transition radiation and transition scattering", *Phys. Rep.*, vol. 49, pp. 1-89, 1979.

[10] J. Pforr, "Strahldynamik und -diagnose am Energierückgewinnenden S-DALINAC", Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2020.

[11] M. Singer, "Entwicklung und Inbetriebnahme eines neuen Datenaufnahmesystems am QCLAM-Spektrometer", Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2020. doi:10.25534/tuprints-00011636

[12] S. Döbert, "Nichtlineare Zeitreihenanalyse der Feldamplitude der supraleitenden Beschleunigungsstrukturen und Aufbau eines HF-Monitorsystems zur zerstörungsfreien Strahldiagnose am S-DALINAC", Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, Germany, 1999.

[13] M. Konrad, "Development and Commissioning of a Digital RF Control System for the S-DALINAC and Migration of the Accelerator Control System to an EPICS Based System", Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2013.

[14] EPICS – Experimental Physics and Industrial Control System, https://epics.anl.gov/

[15] D. Schneider, "Sensitivitätsanalyse der Strahlführungselemente des S-DALINAC unter Anwendung von Polynom-Chaos", master thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2021.