Development and Implementation of an Active Beam-Stabilization System for Electrofission Experiments at the S-DALINAC*

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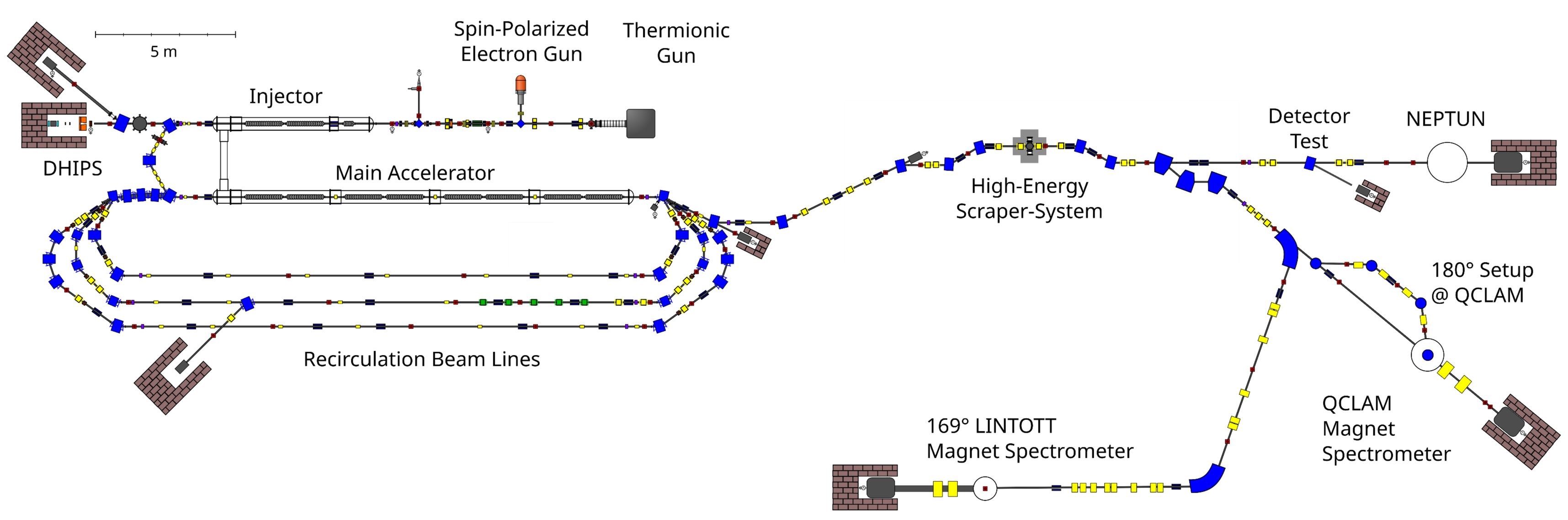
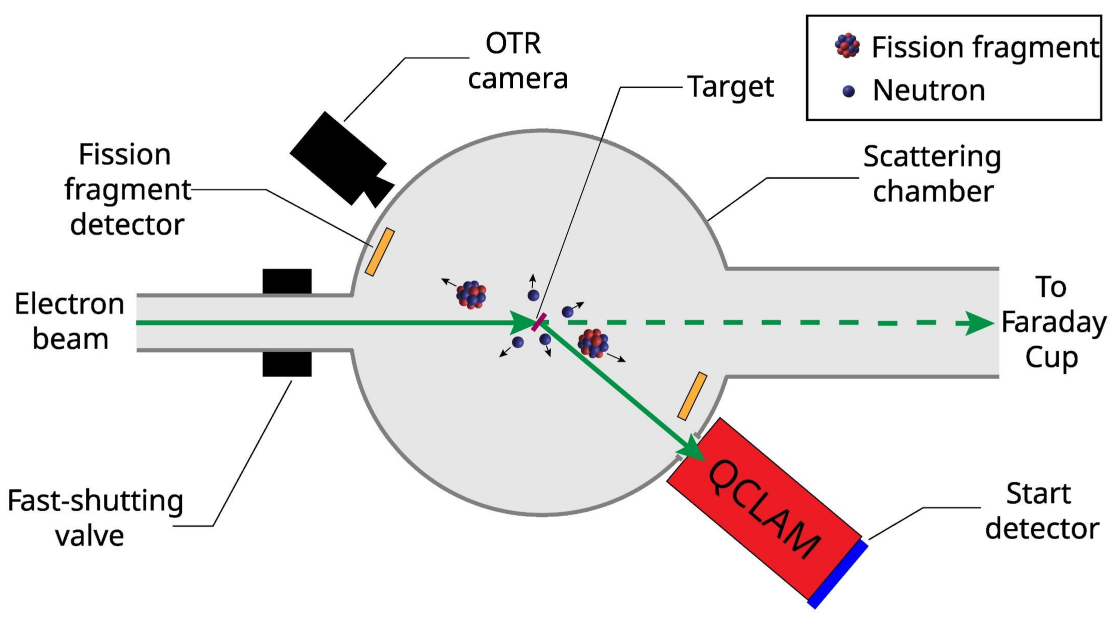
Abstract

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.

Electrofission @ S-DALINAC

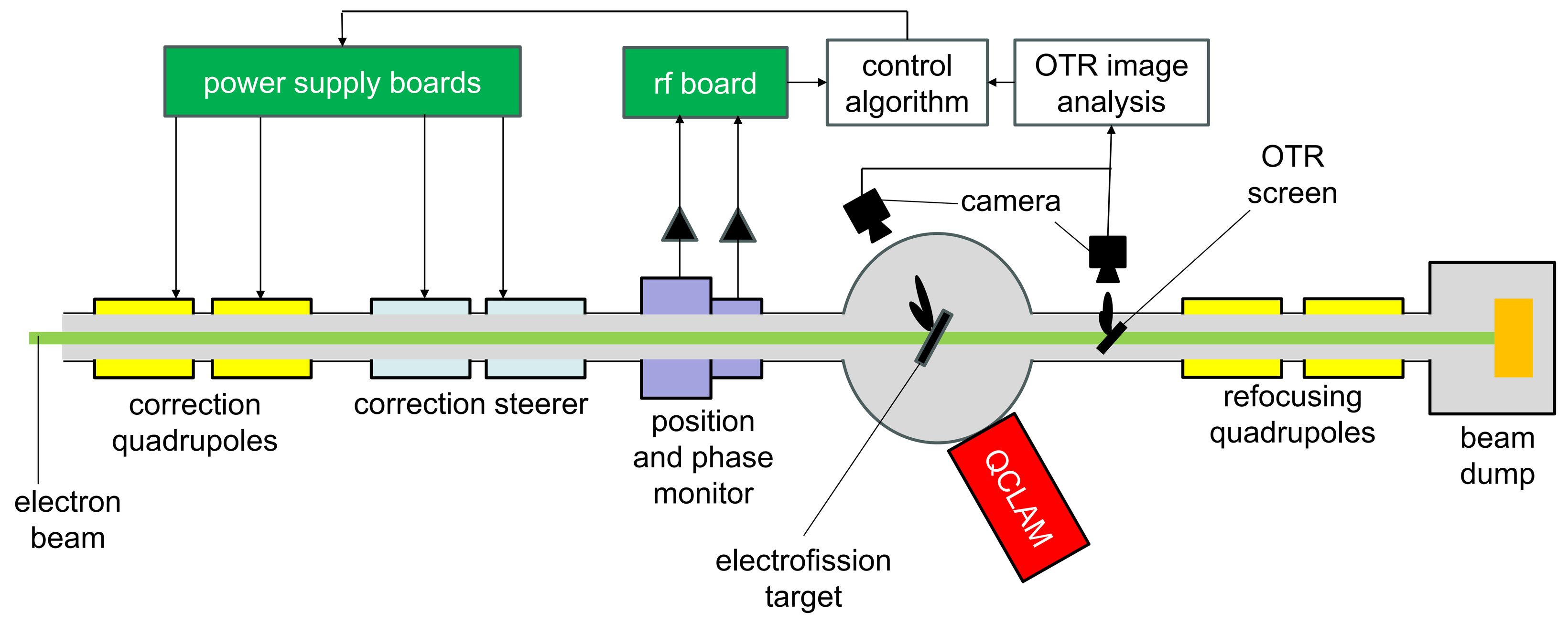


Floorplan of the S-DALINAC. To investigate fission reactions of actinides and their dependence on the excitation energy of the nucleus, electron-induced fission will be employed at the QCLAM magnetic spectrometer. The electron beam will be delivered by the S-DALINAC with a beam current of 3 µA, a frequency of 2.997 GHz, electron energies of the order of 100 MeV and a 3σ beam spot size smaller than 1 mm at the electrofission interaction point.



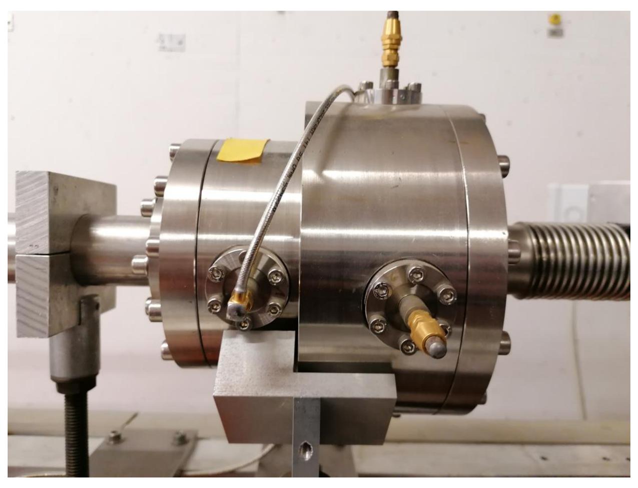
Design of the electrofission setup at the QCLAM. After its interaction with an electron the target nuclei can decay via fission. An accurate description of this process, which is not available up to date, requires the measurement of both fission fragments in coincidence.

Beam Stabilization Setup

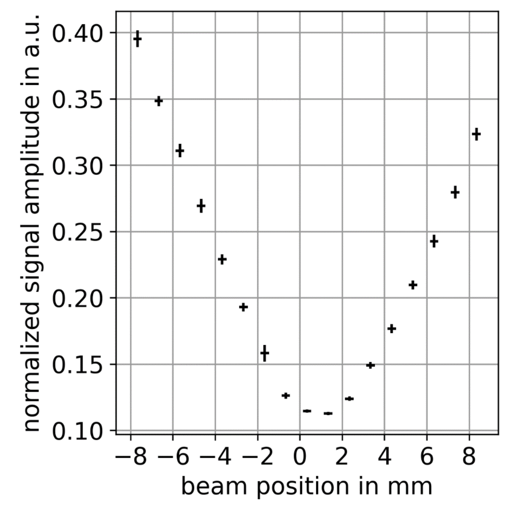


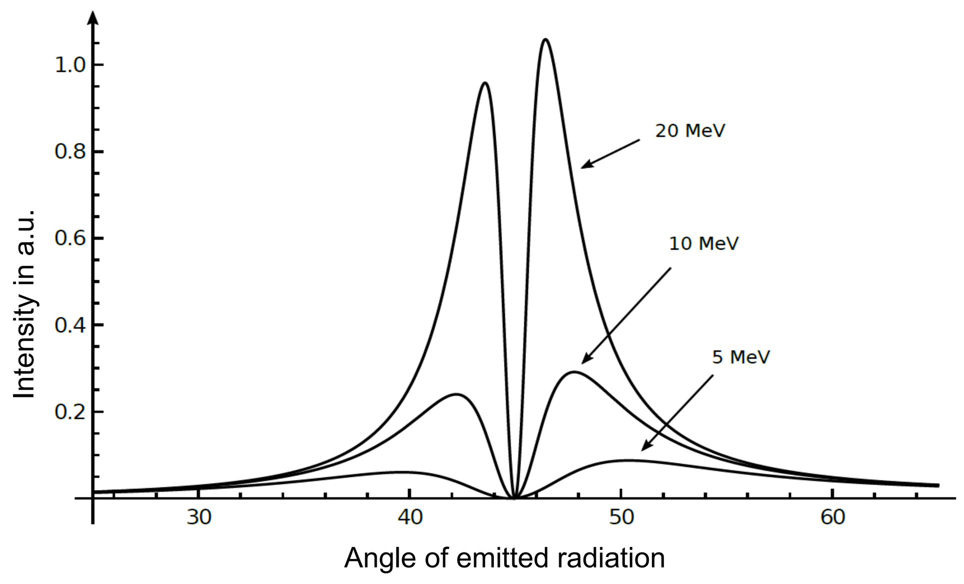
Concept of the beam stabilization setup. If the emitted optical transition radiation (OTR) of the electrofission target can be observed directly, the beam width and center position can be monitored with an ultra-fast camera (option 1). Alternatively, two independent measurements, deduced with a beam position monitor (non-destructive) and a downstream located OTR screen, can be used to approximate the beam profile at the interaction point (option 2). The signal will be processed by the readout electronics to generate a feedback signal for the correction magnets. The feedback control algorithm can be based on a PID controller, a trained AI model or simulations.

Beam Diagnostics Elements



Left: Image of an in-house developed cavity beam position and phase monitor.
Right: Test of this monitor for a beam current of 500 nA. Beam positions with an increment of 1 mm can be resolved.





Backwards angular distribution of OTR at a 45° tilted diagnose screen for several beam energies. The resolution and frequency of the transverse beam profile signal only depends on the OTR intensity and both the camera resolution and frame rate.

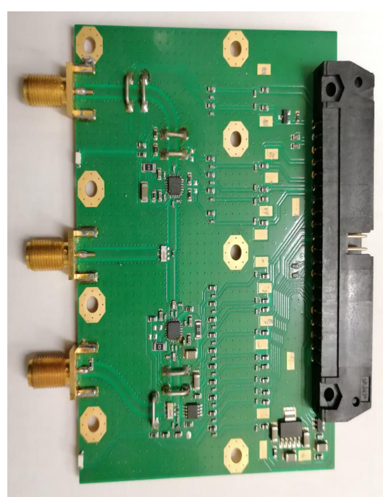
Source: M. Fischer, master thesis, „Design und Aufbau eines Messplatzes zur Strahlqualitätsmessung basierend auf optischer Übergangsstrahlung am S-DALINAC", 2019.

Readout Electronics

Ultra-fast Camera - OTR Setup

- Blackfly S GigE monochrome camera with 0.4 MP
- 500-600 frames per second can be reached
- Fourier-transformation of OTR signal to investigate beam-stability at the S-DALINAC with up to 300 Hz

RF-Board - Cavity BPM

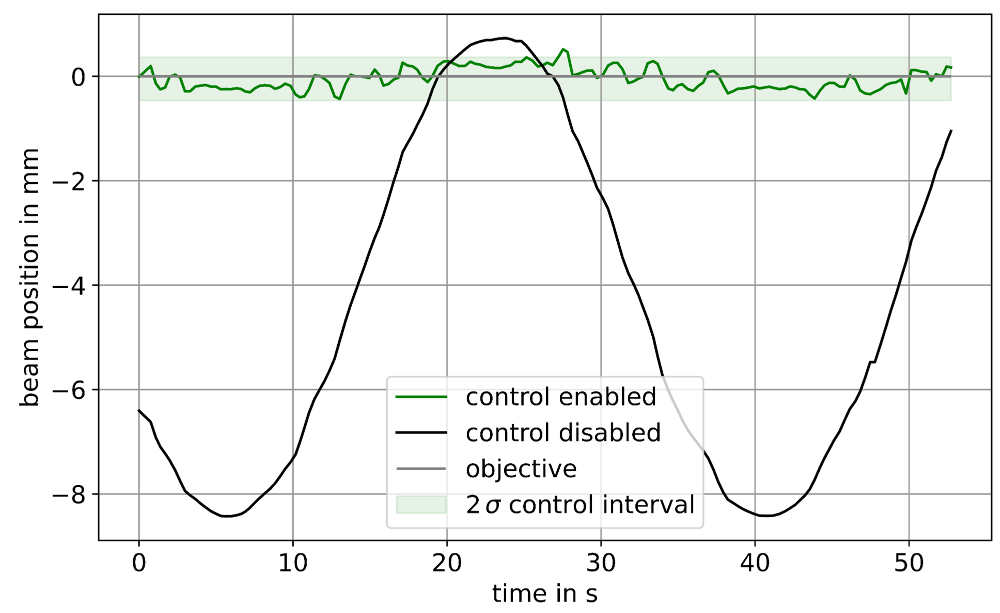


- In-house developed
- 0.4-6 GHz input signal
- IQ demodulator, power detector, IQ modulator
- Calculate beam position from cavity BPM via IQ vector

FPGA - Feedback Control

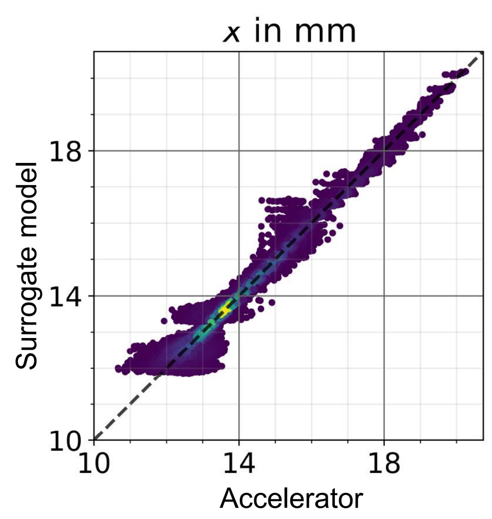
- Faster signal transfer than via control system
- 1 MS/s internal processing rate
- Can implement variety of control algorithms

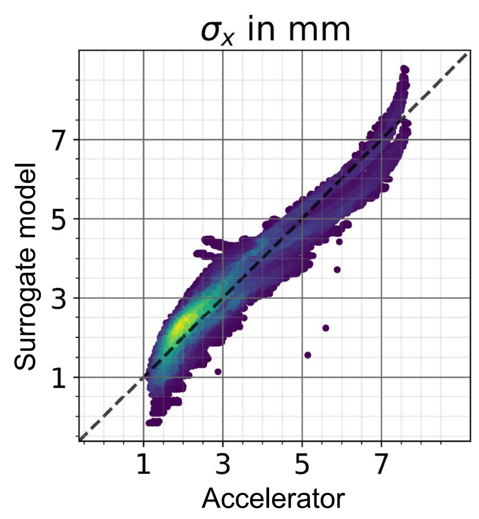
Feedback Control



First test of a beam stabilization with a simulated beam shift (steerer), a correction steerer and a PID controller by monitoring a downstream located beryllium oxide screen. The correction magnet kept the center beam position within a 2σ-interval of ca. 0.8 mm. It is planned to test supervised learning agents as an alternative to traditional PID controllers.

Surrogate models have been used to predict the beam position x and width σ_x in subsystems of the accelerator. It is planned to create a surrogate environment for the beam stabilization setup based on both simulations and machine learning to train, test and refine the selected feedback control algorithms.





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