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HIGH-RESOLUTION LONGITUDINAL BEAM DIAGNOSTICS WITH A FAST FARADAY CUP AT THE UNILAC ACCELERATOR

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Abstract

At the heavy ion accelerator UNILAC at GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, measurements were carried out with a FFC in order to precisely measure the time structure of the particle beam. The FFC offers a highly accurate time-resolved recording of the charge distribution along the longitudinal beam profile. The data obtained in combination with a dipole magnet is used to determine the longitudinal phase space and emittance of the beam. After analysing the measurement results, the method will be integrated into the regular beam diagnostics to ensure continuous monitoring and control of the particle beam during operation. Measurement procedure and results are presented.

INTRODUCTION

The longitudinal charge distribution of a particle bunch is a key property of a beam in ion LINear ACcelerators (LINACs). Due to varying cavity frequencies and acceptance along the accelerator, it is necessary to adjust the longitudinal phase space. This includes knowledge of spread in particle time of arrival with respect to the RF and energy spread.

Typically, one determines the full longitudinal phase space ellipse by measuring one of the projections of the phase space under controlled longitudinal optics settings [1]. This reduces the complexity of longitudinal emittance determination to precise measurement of the longitudinal charge distribution, also referred to as "phase/time of arrival spread" or often just "bunch shape/length".

For this purpose, the UNIversal Linear ACcelerator (UNILAC) has recently been equipped with many Fast Faraday Cups (FFCs) and Bunch Shape Monitors (BSMs). FFCs are variants of the regular Faraday cups optimized for measuring fast time varying charge distributions in the ns regime. This work focuses on a more direct approach to measuring longitudinal emittances using FFCs in dispersive regions. The data presented here has been recorded in July 2025 in a target location called X2 at the UNILAC at GSI with a Radially Coupled Fast Faraday Cup (RCFFC).

This paper provides a brief introduction to the functionality of the FFC, the experimental setup and methods. The focus lies on the ion beam measurement results of the longitudinal phase space distribution performed with the RCFFC.

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FAST FARADAY CUP

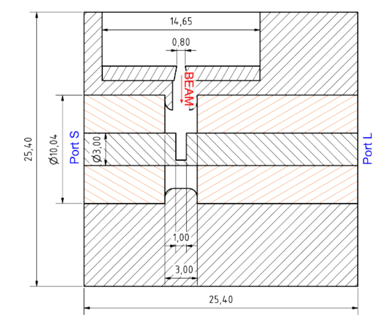

Figure 1: Cross section view of the RCFFC. The beam incidence and port for signal coupling are indicated [2].

The RCFFC has a bandwidth of 5 GHz and a time resolution of 30 ps at $\beta = 0.15$ limited by field dilation effects [3,4] although the RF bandwidth of the FFC structure is higher [5]. It is capable of measuring the longitudinal charge distribution of each bunch along the macro pulse. The beam couples through a blind hole from the side of a coaxial cable through the dielectric medium into the central conductor. In order to minimize the leakage of Secondary Electrons (SEs) , the hole is designed with a width of 1 mm and depth of 2.5 mm, see Fig. 1. Additionally, positive biasing is applied on the collector of the RCFFC to further suppress SEs. The blind hole in the outer conductor of the co-axial is covered with a Titanium-Zirconium-Molybdenum alloy (TZM) disk with a small 0.8 mm hole with the dual purpose of tolerating the heat deposited by the beam and reducing field dilution effects [6].

MEASUREMENTS

The measurements presented in this work were conducted using Ar^{8+} with an ion beam energy of 11.4 MeV/u and an average beam current of 35 µA. The purpose of this measurement is the determination of the longitudinal emittance using dispersion. When charged particle beams pass through a dispersive section, particles with different kinetic energies are deflected on different trajectories. Hence, in circumstances where the dispersion is sufficiently large, the energy spread can be translated into transverse deflection.

The determination of the dispersion in the X2 beamline at the exit of UNILAC (see Fig. 2) is shown in Fig. 3. For this

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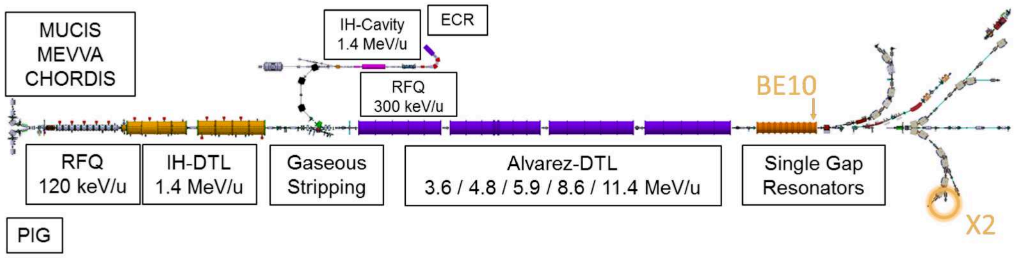

Figure 2: Layout of the UNILAC. The X2 cave and the buncher adjusted for this measurement are highlighted [7].

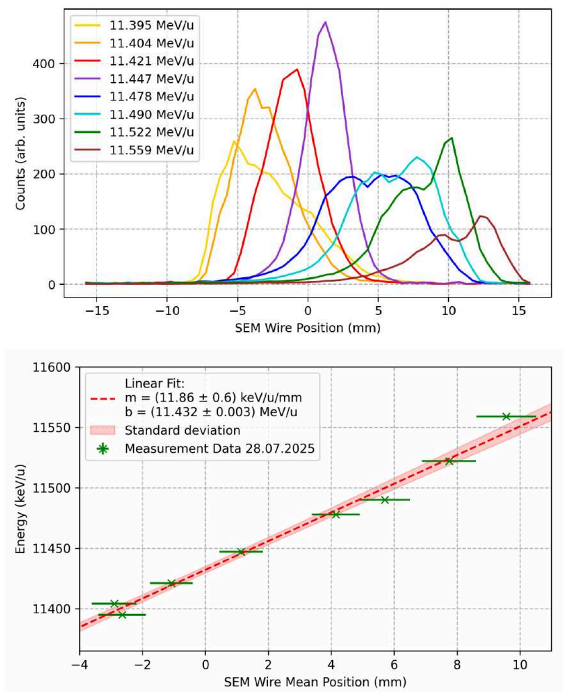

Figure 3: Secondary Electron EMission Grid (SEM-Grid) measurements (top) for the dispersion evaluation in the X2 cave (bottom).

purpose, the beam centre was measured using a SEM-Grid for different beam energies. The used SEM-Grid provides a high resolution and accurate measurements as it consists of 64 tungsten wires 100 µm in diameter and 0.5 mm pitch [8]. The energies were modified by means of a precise tuning of the BE10 single-gap resonator also highlighted in Fig. 2, and were determined using a conventional time-of-flight measurement. The inverse of the dispersion was found to be (11.9 ± 1.2) keV/(u mm) at a beam energy of 11.43 MeV/u. The errorbar for the dispersion is determined by the effect that the transmission for off-energy beam settings decreased.

The RCFFC is measuring the longitudinal charge distribution bunch-by-bunch in the macro pulse as shown in Fig. 4. The evaluation of this measurement is synchronized to the RF. The slightly bipolar shape arises mainly from the AC coupling of the broadband amplifiers (50 MHz - 6 GHz) with additional contributions from SE emission at the bunch tail. In addition, a certain structure can be recognized within the macro pulse, whereby the amplitude of the beam appears to fluctuate periodically with frequencies of 70 kHz and 490 kHz. Potential origins of this phenomenon could be the ion source or mismatched cavities. However, the investigation of these fluctuations extends beyond the scope of this paper and will not be further discussed herein.

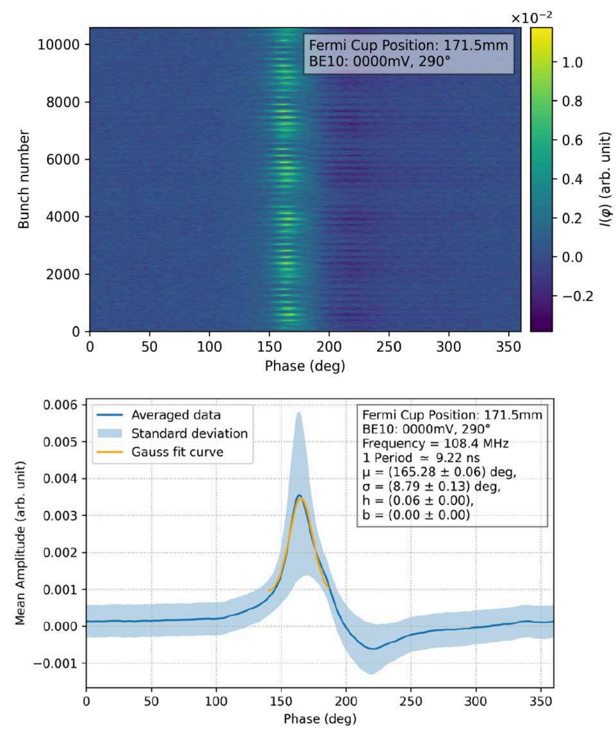

Figure 4: The longitudinal charge distribution of a 35 µA Ar^{8+} in the X2 cave at the UNILAC. (Top) Bunch shape along the macro pulse and (bottom) averaged distribution.

The bunch phase width was measured to be $\sigma_b = 8.8°$, which corresponds to a time structure of $\sigma_b = 225$ ps at a frequency of $f = 108.4$ MHz, corresponding to a period length of $T = 9.22$ ns. However, it should be noted that this only corresponds to the bunch length of a transversal slice of the beam, as only 0.8 mm of the beam is transversally allowed through the hole in the RCFFC. The measurement of the entire beam is shown in Fig. 5. In this instance, the complete longitudinal phase space was analysed using the previously introduced measurement of Dispersion-Assisted Longitudinal Emittance (DALE) [9].

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Due to the high dispersion in the region, the energy spread is translated into transverse deflection, which is now scanned with the stepper motor driven FFC. The FFC position can be associated with specific energies, with higher position values corresponding to higher-energy particles. It should be noted that small phase values correspond to early arrival times. In order to test and verify the possibility of beam manipulation, the single gap resonator BE10 was set to be in bunching mode and the amplitude was gradually increased. For each of these dedicated settings, the entire beam was scanned horizontally with the FFC in order to measure the longitudinal phase space distribution. A selection of the measurements obtained through this method are presented in Fig. 5. The results reveal two distinct central energy peaks that require further investigation.

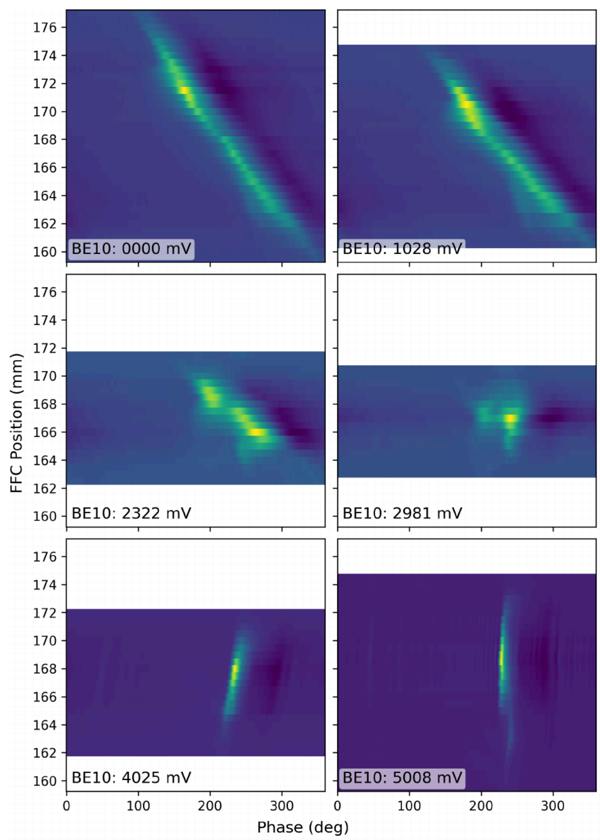

Figure 5: Longitudinal phase space measurements for different buncher amplitudes in bunching mode. The axes range in all plots is the same.

PHASE SPACE TRANSFORMATION

It is evident from the data set that there is a clear and perceptible evolution of the distribution with increasing buncher amplitudes. In bunching mode, the single gap resonator decelerates the particles arriving earlier than the ideal particle and accelerates the particles arriving later. The magnitude of the buncher amplitude directly correlates with the strength of this force acting on the longitudinal ellipse. The beam line between buncher and FFC in X2 is equipped with multiple magnets. For illustrative purposes, a drift of 35 m in the longitudinal phase space is assumed here, and the coupling of the horizontal phase space to the phase is neglected. The drift shifts higher-energy particles to earlier arrival times and lower-energy particles to later ones, giving rise to the observed phase space transformation in Fig. 6.

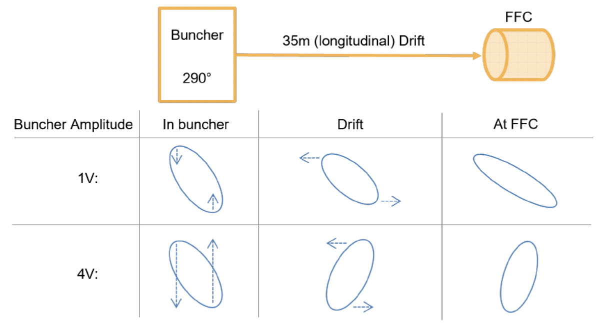

Figure 6: Evolution of the longitudinal phase space ellipse for different buncher settings. The arrows indicate the action of the buncher BE10 and the 35 m long drift.

The targeted beam manipulation is clearly recognisable in Fig. 5, thereby verifying the feasibility of this approach. An optimal reduction of the energy spread of $\Delta E^{3\,\mathrm{V}}_{\mathrm{rms}} = 26 \pm 5$ keV/u was observed at a buncher voltage of approximately 3 V (in-house value) with a phase spread of $\Delta\varphi^{3\,\mathrm{V}}_{\mathrm{rms}} = (23.6 \pm 0.8)^\circ \mathrel{\widehat{=}} (605 \pm 21)$ ps. Near 5 V the phase spread reached its minimum of $\Delta\varphi^{5\,\mathrm{V}}_{\mathrm{rms}} = (7.7 \pm 0.5)^\circ \mathrel{\widehat{=}} (197 \pm 12)$ ps with $\Delta E^{5\,\mathrm{V}}_{\mathrm{rms}} = (45 \pm 7)$ keV/u, demonstrating the sensitivity of the longitudinal beam dynamics to the applied buncher settings. A maximal energy spread of $\Delta E^{0\,\mathrm{V}}_{\mathrm{rms}} = (61 \pm 9)$ keV/u was observed while the buncher was in pause. The values refer to the projections of the entire phase space.

CONCLUSION & OUTLOOK

The longitudinal phase space at UNILAC was successfully characterized using dispersion-assisted longitudinal emittance measurements with the RCFFC. By systematically varying the buncher settings, the phase space distribution could be manipulated, and the expected changes in the longitudinal charge distribution were clearly observed, confirming the validity of the method.

The demonstrated beam manipulation potentially enables improved injection into theSchwer-Ionen-Synchrotron 18 (SIS18). Outlook of this work is to track the measured longitudinal distribution back to the transfer channel and propagate it until the synchrotron. This would allow the beam to be adjusted to minimise the energy spread and approach ideal injection conditions.

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