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BUNCH SHAPE MEASUREMENTS AT THE GSI CW-LINAC PROTOTYPE

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Abstract

The existing GSI accelerator will become the injector for FAIR [1-5]. To preserve and enhance the current experimental program at UNILAC, a new Linac is under development, which shall run in parallel to the FAIR injector, providing cw-beams of ions at energies from 3.5 – 7.3 MeV/u [6, 7]. For this cw-Linac a superconducting prototype cavity has been developed and was first operated with beam in summer 2017 [8]. The resonator is a cross-bar H-structure (CH) of 0.7 m length, with a resonant frequency of 216.8 MHz. It has been installed behind the GSI High Charge State Injector (HLI), which provided 108 MHz bunches of 1.4 MeV/u Ar6+/9+/11+ ions at a duty cycle of 25%. Due to the frequency jump and small longitudinal acceptance of the CH, proper matching of the HLI beam to the prototype was required. The bunch properties of the injected beam as well as the effect of different phase- and amplitude-settings of the cavity were measured in detail with a bunch shape monitor (BSM) fabricated at INR, Moscow [9], while the mean energy was analyzed by time-of-flight method with phase probes. In this contribution, the bunch shape measurements are described and the capabilities of the used BSM measurement principle are discussed.

INTRODUCTION

The measurement of the bunch shape behind an accelerating cavity is - together with the transmission and the transverse beam parameters - a key analysis of the accelerator characteristics as well as of the quality of injected and transported beam. Especially in case of the new, highly efficient, CH resonators [10], the precise knowledge of the cavity parameters (rf-power, sync. phase) is essential to avoid beam losses and/or beam deformation, resulting in losses in the next accelerating structure. The precise matching from one cavity to the other is even more important for the new GSI cw-Linac, which is designed to provide the beam for the previous UNILAC experiments and to serve at the same time as a backup for the UNILAC as an injector for SIS18. The cw-Linac will provide ion beams over a large energy range (3.5 – 7.3 MeV/u) using the so called equidistant multigap structure (EQUUS) particle dynamics [11], which is - at least for a chain of cavities operated in this mode - strongly dependent on proper adjustment of rf-power and synchronous phase. For the test of these cavities, it is desirable to measure the bunch length with a sufficiently fast device to cope with bunch lengths in the range of several hundred picoseconds. Moreover, looking at the energy range of the cw-Linac prototype (1.4 – 1.86 Mev/u) it is evident that the beam is slow enough to cause a significant effect by the forward and backward electrical field of the bunches on a conventional capacitive pickup, resulting in strong prolongation of the pickup signal. Therefore devices using secondary electrons, generated either from residual gas or a wire introduced in the beam, are the most reasonable choice for detection. At GSI a non-destructive BSM has been developed, which extracts - similar like an Ionization Profile Monitor - electrons from residual gas collisions from the beam line and uses energy separation followed by an rf-deflector to produce an image of the bunch on a phosphor screen [12]. Although this device has been well tested and showed good performance, it turned out that (at its current stage) some optimization work for practical operation is required. As an alternative, an established device, developed at the Institute for Nuclear Research (INR) Moscow by A. Feschenko was purchased for the UNILAC/cw-Linac and will also be used in the FAIR proton-Linac.

THE BUNCH SHAPE MONITOR

Figure 1 shows the basic principle of the INR BSM. The beam is longitudinally scanned with a Tungsten wire, placed at the beam axis on negative potential (–10 kV).

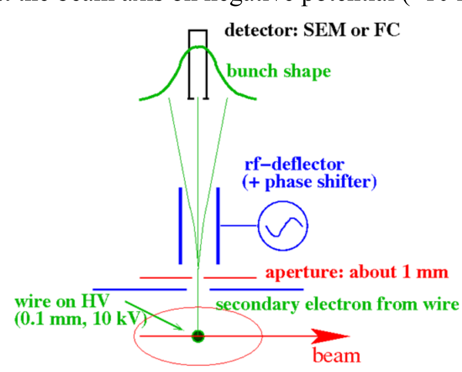

Figure 1: Principle of the bunch shape monitor.

By interaction of the ions with the metal surface secondary electrons are emitted, which are extracted towards ground potential. The electrons pass through an

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rf-deflector (in combination with an Einzellens), operating at the frequency of the accelerating cavity (HLI, 108.408 MHz). They can only pass through the following vertical slit, if the deflector field is at zero-crossing. A phase shift of the deflector-rf relative to the Linac-rf in *n* steps provides therefore a scan of the bunch with a bin-size corresponding to *n*. After energy separation in a magnetic deflector, the current behind the SEM detector is plotted as a function of rf-phase. In this way, the spatial information of the particle distribution in the bunch is transformed into phase information relative to the rf-period of the accelerator. It is obvious from this point of view, that the BSM will produce two images of the bunch, when set to a span of 360°, therefore it has to be set - after a first coarse measurement - to a reasonable phase span. While the binning depends on the number of phase steps, the phase resolution depends basically on the width of the slit and the deflector voltage. Maximum (reasonable) resolution for our device (0.5 mm slit) was 1°. The BSM can - as a matter of principle - not be considered as a non-destructive device, but it was found to be an excellent tool for Linac commissioning. Moreover, it could be shown at CERN Linac4 [13], that the BSM can be used to determine the longitudinal emittance by phase space tomography. A test of this procedure is also planned at GSI during upcoming beam times.

TEST SETUP FOR THE CW-LINAC

Figure 2 shows the experimental setup at the cw-Linac test stand. A 1.4 MeV/u beam from the GSI HLI injector was used, providing argon ions with various A/q values ($Ar^{6+/9+/11+}$) at a duty cycle of 25%.

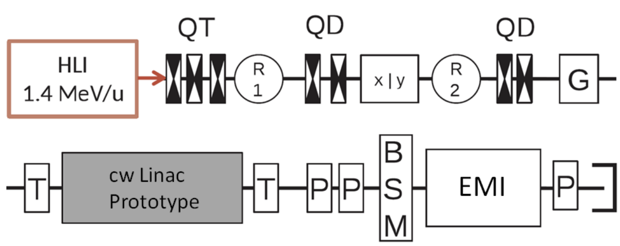

Figure 2: Layout of the test beamline of the cw-Linac prototype (demonstrator). Beam from left to right, upper to lower. QT and QD = quadrupoles, R = rebunchers, x | y = steerers, G = grid, T = macro pulse beam transformer, P = phase probe, EMI = emittance scanner [8].

After optimization of the rebuncher settings for injection, the rf-power and phase of the demonstrator were varied to check the effect on output current, bunch structure, particle energy and transverse emittance. In this way, the characteristics and design values of the prototype could be verified, the measurements are described in detail in [8].

During preparation, the transport of the electron beam in the BSM had to be optimized. This is done by heating the tungsten wire (on –10 kV potential) with a current of max. 1 A. In this case a DC current of thermal electrons is extracted, to simulate the beam. The slit behind the deflector as well as the SEM detector are equipped with phosphor screens, which can be observed by cameras, while varying the settings of lenses and deflectors to optimize the beam transport. Figure 3 shows a picture of the BSM installed in the beam line.

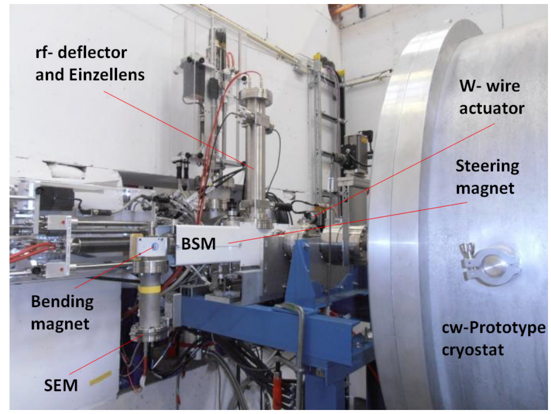

Figure 3: BSM in the cw-Linac test beam line.

BUNCH MEASUREMENTS

In a first step, it was required to focus the beam longitudinally on the entrance of the prototype. To also test the capabilities of the BSM, the bunching phase of R1 was determined by doing a phase sweep until neither energy gain nor energy loss occurred. Figure 4 shows the measured bunches together with the beam without rebunching, the bunching phase is located, where the centres of both curves coincide, in this case around 23°.

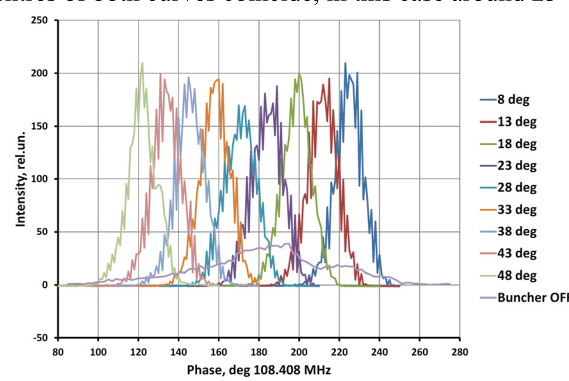

Figure 4: Bunch shapes for different phases of the rebuncher R1.

Figure 4 illustrates that the BSM can also be used for energy measurements with high accuracy, if the absolute energy is once calibrated with a spectrometer or time-of-flight between two phase probes. It is clear, that only measurements with identical parameters (wire potential, steering voltage etc.) can be compared. Slight deviations can occur from superposition of the bunch potential to the wire potential, which is described in [14], but this effect is negligible at the given beam parameters.

The bunching phase can be determined in a more accurate way, if the centre phase value of the bunches is plotted as a function of buncher phase for different buncher voltages, like shown in Fig. 5. The curves of the different voltages intersect at 26°, which has to be

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considered as the nominal buncher phase. With this measurement, also the effective bunching voltage can be determined in a simple and accurate way.

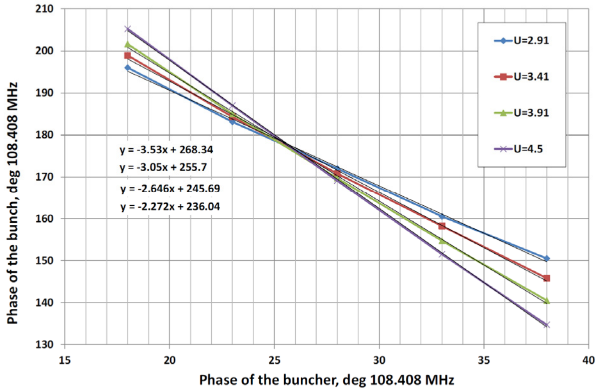

Figure 5: Determination of nominal buncher phase.

During the cw-Linac prototype tests, the buncher phases were adjusted by doing phase sweeps measuring the beam energy by TOF. To match the beam longitudinally to the CH, the R2 amplitude was increased until the waist at the BSM position had the same width as with R2 switched off (overfocusing). Since the prototype cavity entrance was located more or less exactly at half the distance from R2, compared to the BSM, the waist was transferred to the CH entrance in this way. Figure 6 shows a comparison of the beam with R1 and R2 switched off and the bunched beam for the matched case.

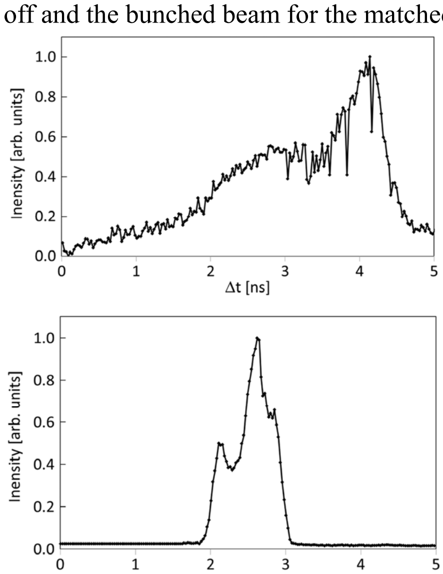

Figure 6: Upper: HLI beam at 1.366 MeV/u, without rebunching. Lower: Same beam with R1 and R2 set for injection into the prototype [8].

One of the key measurements with the BSM was to set the prototype to the nominal rf-power for 3.5 MV/m (Ar^{9+}) and to perform a phase sweep, as shown (representative for the numerous bunch measurements) in Fig. 7. It was found, that the bunch length is very sensitive to phase changes, but - due to the EQUUS dynamics - not the transmission. A change of the rf-phase by 30° leads to an increase of the bunch length by a factor 4, while the transmission (as detected with a current transformer directly behind the cavity) is not affected over a wide phase range.

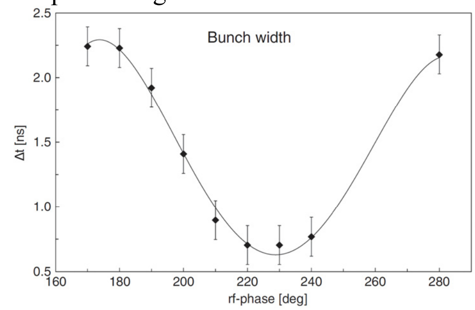

Figure 7: Phase scan with corresponding bunch length (FWHM) of the cw-Linac prototype at 3.5 MV/m for Ar^{9+}-ions [8].

In parallel to measurements with the BSM, the bunches were detected with phase probes and a Fast Current Transformer (FCT) [15]. To illustrate the resolution of the BSM, Fig. 8 shows a comparison. The resolution of the phase probe and FCT is actually too low, to detect any difference between the bunch shapes shown in Fig. 6.

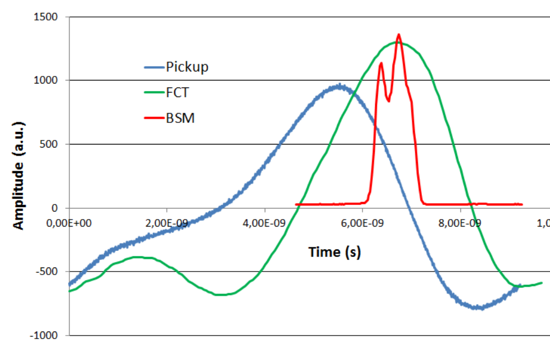

Figure 8: Comparison of identical bunches, measured with BSM, phase probe and FCT.

SUMMARY AND OUTLOOK

The prototype cavity for the new GSI cw-Linac has been commissioned successfully. It could be demonstrated, that it fulfils the design criteria and even exceeds them with respect to transmission and beam quality over a wide energy range. The INR BSM was a key diagnostics during these measurements. Exact determination of the bunch length and shape is essential for the operation mode of the cw-Linac, so the commissioning of the whole machine is strongly dependent on bunch shape measurements. The situation at the FAIR proton-Linac is similar, here a comparable BSM will be used. In connection with the upcoming measurements at HLI, the possibility of longitudinal emittance measurements by phase space topology will be investigated.

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