APPLICATION OF BEAM DIAGNOSTICS FOR INTENSE HEAVY ION BEAMS AT THE GSI UNILAC

W. Barth, L. Dahl, J. Glatz, L. Groening, S. Richter, S. Yaramishev
Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

Abstract

With the new High Current Injector (HSI) of the GSI UNILAC the beam pulse intensity had been increased by approximately two orders of magnitudes. The HSI was mounted and commissioned in 1999; since this time the UNILAC serves as an injector for high uranium intensities for the synchrotron SIS. Considering the high beam power of up to 1250 kW and the short stopping range for the UNILAC beam energies (< 12 MeV/u), accelerator components could be destroyed, even during a single beam pulse. All diagnostic elements had to be replaced preferably by non-destructive devices. Beam transformers instead of Faraday cups mainly measure the beam current, beam positions are measured with segmented capacitive pick-ups and residual gas monitors instead of profile harps. The 24 installed phase probes are also used to measure widths and phase of the bunches, as well as beam energies by evaluating pick-ups at different positions. The residual gas ionisation monitors allow for on-line measurements of beam profiles. The knowledge of the real phase space distribution at certain position along the linac is necessary for optimising the machine tuning, for the improvement of the matching to the synchrotron, and for a better understanding of beam dynamic issues under space charge conditions. The paper reports the application of different beam diagnostic devices for the measurement of transverse beam emittances at different UNILAC beam energies and at different beam intensities. Additionally, measurements of the bunch structure after the HSI and the design of a new device for the measurement of the longitudinal emittance at the end of the UNILAC are included.

INTRODUCTION

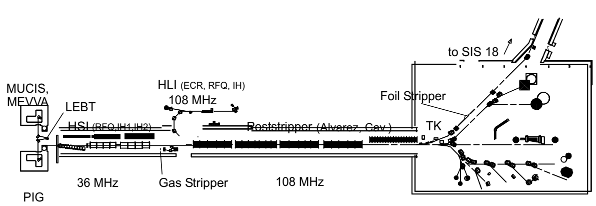

Fig. 1: Schematic overview of the GSI UNILAC.

The GSI-UNILAC is specified to deliver up to $4{\cdot}10^{10}$ U^{73+} particles to the heavy ion synchrotron (SIS) during 100 μs, whereby the HSI accelerates 15 emA $^{238}U^{4+}$. The required beam parameters (for the uranium case) are summarized in Table 1. In 1999 the UNILAC (see Figure 1) underwent a renewal of its prestripper section to increase the ion beam current to I = 0.25 A/q (emA) for mass over charge ratios of up to 65. The high

Table 1: Specified beam parameters along the UNILAC.

	HSI entrance	HSI exit	Alvarez entrance	SIS injection
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{73+}$
El. Current [mA]	16.5	15	12.5	4.6
Part. per 100μs pulse	$2.6{\cdot}10^{12}$	$2.3{\cdot}10^{12}$	$2.8{\cdot}10^{11}$	$4.2{\cdot}10^{10}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4
ΔW/W	-	$4{\cdot}10^{-3}$	$\pm1{\cdot}10^{-2}$	$\pm2{\cdot}10^{-3}$
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5

current injector HSI consists of ion sources of MEVVA-, MUCIS- or Penning-type, a mass spectrometer, and a low energy beam transport system (LEBT). The 36 MHz RFQ accelerates the ion beam from 2.2 keV/u to 120 keV/u. The matching to the following IH-DTL is done with a short 11 cell adapter RFQ (Super Lens). The IH-DTL consists of two separate tanks accelerating the beam to the full HSI-energy of 1.4 MeV/u [1]. Before injection into the Alvarez accelerator the HSI-beam is stripped (gas stripper) - charge analysis is indispensable. A five stage accelerator provides seven discrete beam energies in the range of 3.6 to 11.4 MeV/u, the following 10 single gap resonators allow any energy up to 13 MeV/u. In the transfer line to the synchrotron at 11.4 MeV/u a foil stripper and another charge state separator system is in use.

OPERATING BEAM DIAGNOSTICS

Table 2: Number of beam diagnosis devices in the UNILAC.

Element	Number	Resolution
Faraday Cups	73	100 nA (high power capable)
Current Transformers	45	100 nA (100 kHz)
Profile Grids	103	≥ 1 mm
Capacitive Pick ups (to determine positions)	34 25	ΔW/W = 0.1 %
Emittance Meas. Device	8	variable
Bunch Shape Monitors	2	25 ps (0.3°)

The wide spread of beam intensities – from pA up to mA demands for a very versatile set of different beam diagnostics elements. To measure the different beam properties such as position, profile, intensity, energy, transverse emittance and, bunch shape various beam diagnostics elements (listed in Table 2) are employed.

The Faraday cups serve primarily as beam stoppers, and secondarily as diagnostics devices. Current transformers and profile grids are used for beam set-up and tuning. The capacitive pick-ups measure the beam energy by a time-of-flight technique; the sampled signal of up to two pick-ups can be displayed on a video screen.

Using this visualization it is possible to evaluate the shape and stability of the macro-pulse.

The measurement of the transverse beam emittances is either used during machine development.

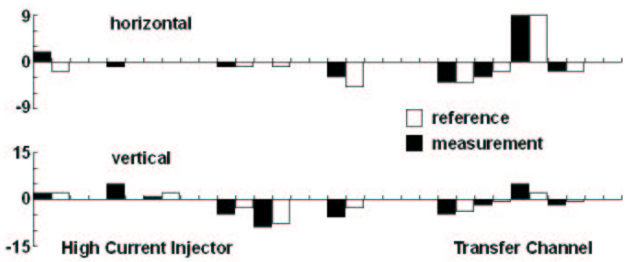

Fig. 2: Online monitoring of beam position with the rf-bunch pick-ups at the HSI and transfer channel; the measured positions and a stored reference are represented.

BEAM DIAGNOSTICS FOR HIGH CURRENT OPERATION

If the HSI delivers highly intense uranium beams, the power stored in one pulse (100 µs) can easily destroy any conventional beam destructive diagnostics element. So either the beam intensity has to be reduced to perform the measurements, or dedicated non-destructive measurements have to be used [2]. At the UNILAC both paths are followed: non-destructive devices such as the current transformers as well as residual gas monitors are installed. An online surveillance system automatically reduces the frequency and the length of the beam pulses. This keeps the deposited power well below any destruction threshold.

The outmost number of rf-bunch pick-ups are 4-segmented probes, which allow to derive the beam position by digitizing the power of the 6th harmonic of the rf-frequency. Next to this function the current transformers are also the basis of the online transmission surveillance system. This surveillance system is directly linked to the control system and can monitor each of possible different ion beams independently. If a significant beam loss is detected, an interlock signal is generated that cuts off the beam pulse within less than 10 µs.

EMITTANCE MEASUREMENTS

Measurements of transverse emittances for the several energy steps of the HSI (and at 11.4 MeV/u) were done exclusively with a slit-grid device for short pulses. The emittances were measured in the LEBT-section, for 120 keV/u, 750 keV/u and 1.4 MeV/u the beam was transported to a measurement device in the gas stripper region; another device is placed after the Alvarez. Fig. 3 summarises the measured emittance data for an Ar^{1+} beam with 10 mA at RFQ injection and 6.5 mA at the HSI exit. The Ar^{10+} current (after stripping and charge state analysis) came up to 7 mA by gas stripper density

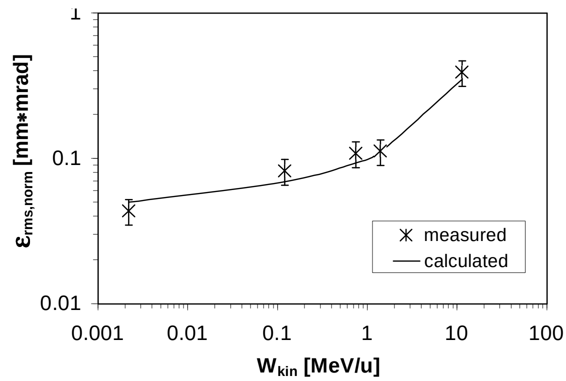

Fig. 3: Measurement of the emittance along the UNILAC.

variation. The measurements agreed to the calculation, if a measuring error of about ±15 % is taken into account.

For high current operation a pepper-pot system capable to measure the transversal emittance within one macro-pulse was used, for more details see [2].

As an example Fig. 4 represents the variation of the beam emittance influenced by space charge forces due to an intensity increase of an Ar^{10+}-beam. The intensity variation is done in the LEBT section. Whereas the beam divergence measured after the prestripper does not change, a significant dependence of the beam distribution after stripping and transport to the poststripper takes place. Thus intensity depending matching to the Alvarez accelerator is inevitable.

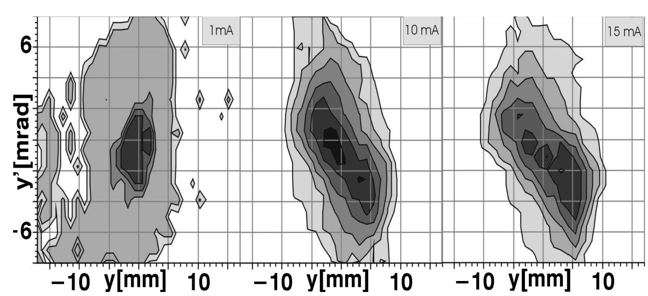

Fig. 4: Measured emittance as a function of Ar^{10+}-intensity.

BUNCH SHAPE MEASUREMENT

Bunch shape measurements were done using diamond detectors, whereas the ion beam (here Ar^{1+}) passes a thin Au-foil – the "Rutherford"-scattered particles hit the detector below a small angle. The bunch shape is obtained by measuring the arrival time of the particles against a reference [1]. It was even possible to observe the typical "zero current" phase space distribution in longitudinal plane, leading to intensity peaks at the centre and at the beginning (resp. at the end) of the measured bunch shape.

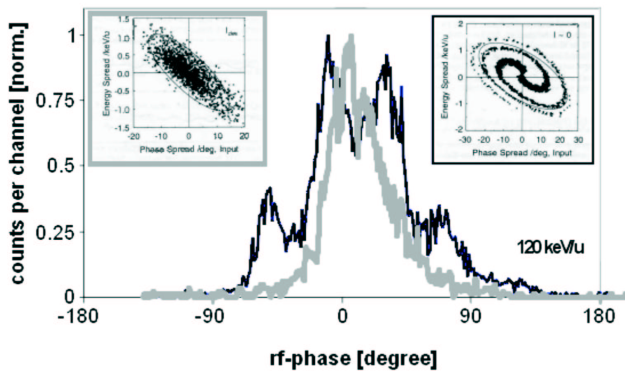

Fig. 5: Bunch shape measurement for high and low currents; additionally the corresponding calculated longitudinal beam emittances are represented.

ONLINE MEASUREMENT OF THE LONGITUDINAL EMITTANCE

At the injection to the SIS the total momentum spread must be lower than 0.1%. The efficiency in setting the longitudinal beam focusing is considerably increased if an image of the longitudinal phase space distribution is available during the setting procedure. The proposed set-up [4] for such an online measurement comprises an iris, magnetic bends, a vertical rf-chopper at 108 MHz, and a beam profile screen (Fig. 6).

The method is based on the transformation of the longitudinal particle coordinates into transverse coordinates. With the dispersion D_x after bending magnets the particles energy deviation dp/p_i is transformed at first order into the horizontal position

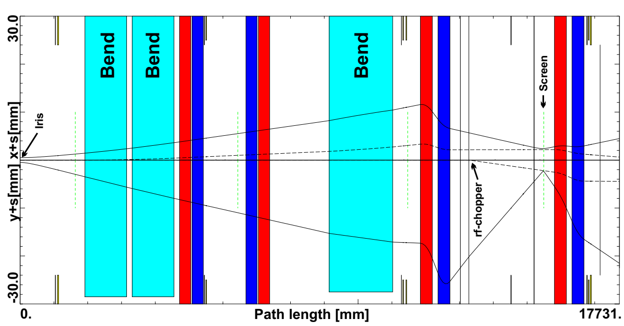

Fig. 6: Set-up for measurement of the longitudinal phase space distribution with horizontal (upper) and vertical (lower) beam envelopes (solid) and design orbits (dotted)

$$x_i = D_x \cdot dp/p_i + O[(\varepsilon_{x,i}\beta_x)^{1/2}].$$

If the bunch passes a vertical rf-chopper the particles longitudinal phase $\varphi_{l,i}$ is transformed into a vertical kick, being a vertical offset y_i after a subsequent drift L.

$$y_i = L\,[\text{const. } U_{gap} \cdot \sin(\varphi_{l,i})] + O[(\varepsilon_{y,i}\beta_y)^{1/2}],$$

where U_{gap} is the peak voltage in the chopper, $\varepsilon_{xy,i}$ is the single particle emittance, β_{xy} is the β-function at the screen, and O indicates terms that scale with the expression within the brackets. The constant includes the beam parameters and the geometry of the chopper. To obtain simple linear transformations, the transverse beam emittances are limited by an iris before the first bend. Additionally, a small beam spot, i.e. β_{xy}, must be set at the screen while the chopper is not active (Fig. 6, left). The energy spread dominates the minimized spot size.

Afterwards the vertical rf-chopper is activated (Fig. 7, right) in order to fully image the longitudinal phase space distribution at the position of the chopper. The obtained resolution is given by the opening of the iris, by the dispersion, and by the resolution and size of the beam profile screen. Using an iris of 1 mm and an inter-wire distance at the screen of 1 mm, we expect for an energy of 11.4 MeV/u a resolution of 10 keV/u and 3º (108 MHz) in energy spread and in phase spread, respectively.

The set-up for the longitudinal emittance measurement will be installed and commissioned in June 2003.

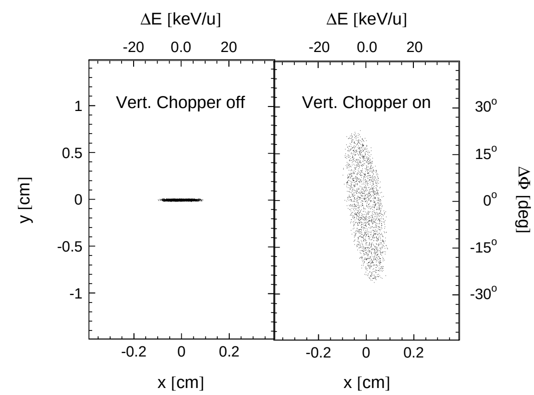

Fig. 7: Simulated beam spot image at the screen for a minimized beam size while the vertical rf-chopper is not active (left) and while it is active (right). The horizontal axis corresponds to the energy spread and the vertical axis corresponds to the phase spread (108 MHz).

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