LONGITUDINAL EMITTANCE MEASUREMENT USING PARTICLE DETECTORS

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Abstract

A device for accessing the longitudinal phase space at low energy sections (1.4 MeV/u) of the GSI heavy ion LINAC is presented. The interceptive measurement is based on the coincident detection of single particles by means of two detectors: The first detector provides measurement of secondary electrons emitted from a thin Al-foil by the impinging ion beam. Secondly, after a drift beam particles are registered directly by a fast diamond detector. This contribution describes the measurement setup in detail including the principle of particle number attenuation by Rutherford scattering in the Ta foil. The achievements concerning the required timing resolution are presented and the investigations are accompanied by recently recorded data. Finally an outlook towards post-processing is given.

MOTIVATION

The existing facility at GSI will be used as injector for the future project FAIR which requires optimizations of the existing accelerator facility. Depending on the kind of a certain optimization crucial information may be obtained from beam diagnostics. The device presented is located at the linear acceleration UNILAC and is aimed at providing information about the longitudinal phase space in order to improve injection into the Alvarez section (Fig. 1). Due to the location in front of the Alvarez tank spatial constraints led to a novel approach that is based on the time-of-flight (TOF) between two particle detectors [1].

WORKING PRINCIPLE

The measurement setup can basically be divided into three crucial parts. At first a mechanism has to provide feasible particle number attenuation to satisfy single particle coincidence measurements. Secondly, two timestamps are needed to account for the energy of the particle. Lastly,

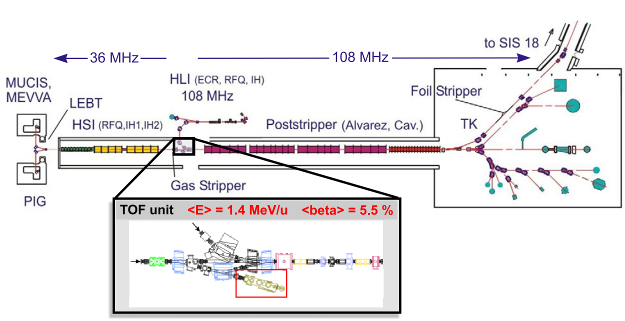

Figure 1: Setup located at GSI UNILAC after IH structures, accessible by the high current injector.

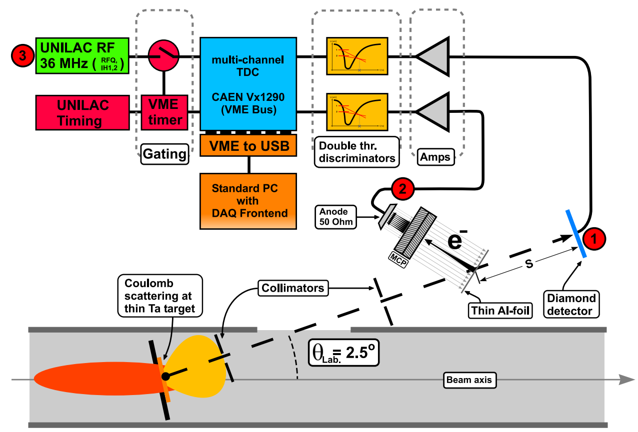

Figure 2: Device schematics. Single particles are detected indirectly at MCP module (2) and directly at diamond detector (1). UNILAC rf (3) is used as timing reference.

a method to determine the relative phase information is required to complete the longitudinal degrees of freedom within the phase space. The schematic of the measurement setup is depicted in Fig. 2.

Particle number attenuation is accomplished in two stages. Once the beam enters the device attenuation is carried out by coulomb scattering using a thin Ta foil of 210 $\mu g/cm^2$ and selecting scattered particles under an laboratory angle of $2.5°$ with respect to the beam axis. Two plates with $\varnothing$ 0.5 mm and 1 mm at a distance of $155mm$ act as a collimator to achieve a small solid angle of $\Omega \approx 10^{-4}$. This assumes incoming beam intensities that have already been lowered to several μA in order to prevent damages of the Ta foil. This allows for a single particle coincidence per bunch at maximum in conjunction with coulomb scattering utilising the aforementioned selection of particles under a certain solid angle. Primary beam attenuation needs different approaches for low current and high current measurements. The attenuation of the primary beam from a maximal current of $\approx 10\ mA$ to about $10\ \mu A$ is done using transverse defocusing at different locations along the UNILAC. By this space charge effects along the Linac structures are influenced. Variation of the gas pressure inside the stripper section provides an additional parameter to adjust the primary beam attenuation which is used in particular at high current measurements.

The detector setup consists of a Microchannel Plate (MCP, *Hamamatsu F4655-13*) and a diamond detector separated at 80 cm, the drift length relevant for the TOF.

Due to the high stopping power at 1.4 MeV/u, it is not possible to have a direct measurement of the traversing ions in both detectors. Therefore the MCP module has been designed to provide an indirect timing signal by measurement of secondary electrons emitted by a thin Al foil (9 $\mu g/cm^2$) which is exposed to the particle trajectory. A potential of $-2\ kV$ with respect to the MCP front is applied to the Al foil. Electrons emitted from the Al foil are accelerated towards the MCP working at a potential of $\Delta U_{MCP} = -1.9\ kV$ and are assumed to have a sufficiently sharp peaked velocity distribution to legitimate a constant time offset imposed by their TOF. Signals are taken at the MCP anode using a bias tee connected to ground preventing damages of the DAQ electronics due to possible charge accumulation.

Eventually the ions are detected directly at a diamond detector. The diamond detector has a diameter of 8 mm with a thickness of 200 μm and is supplied by 200 V. Both detector signals are further processed by double threshold discriminators [3] and subsequently fed to a high resolution TDC (CAEN V1290). Derived from the UNILAC rf of 36.136 MHz a logical pulse representing the period length is generated and recorded by the TDC. To reduce data overhead a prescaler of 10 is used on the regular rf data by analog gating. Linear regression is applied on the stable timing data to improve precision. The relative phase information is acquired by the time difference of the diamond time information with respect to the UNILAC rf reference. A custom-made VME beam timing module provides the macro pulse start timing.

The longitudinal phase space information is reconstructed by transformation of the TDC data into the relevant scales and subsequent filling appropriate histograms. With $\Delta t = t_{Dia} - t_{MCP}$ and assuming that $\Delta E \ll \langle E \rangle$ the relative energy deviation in linear approximation is given by

$$\frac{\Delta E}{\langle E \rangle} \approx \frac{dE}{E}\bigg|_{E=\langle E \rangle} = -2\frac{dt}{t}\bigg|_{t=t_{\langle E \rangle}} \approx -2\frac{\Delta t}{t_{\langle E \rangle}},$$

where $\langle E \rangle = E(t_{\langle E \rangle})$ is the mean energy and $t_{\langle E \rangle}$ is the TOF for a particle at mean energy. To account for relative cable offsets and latency effects at the MCP module, the design energy of 1.4 MeV is used a priori, i.e. data evaluation is based on central moments. It should be noted however that without linear approximation it is particular difficult to determine the correct phase space since it is not invariant under translation in $t_{\langle E \rangle}$.

MEASUREMENT EXAMPLE

An example of data recorded with a high current setting is depicted in Fig. 3. The lower left pad shows the actual recorded data with its projection on bunch structure (upper left) and its relative energy deviation (lower right). In the upper right pad the expected longitudinal phase space at Alvarez injection has been calculated using the in-house Dynamion code. The measured phase space deviates significantly in the energy spread compared to the phase space received by the tracking code and gives a hint for the experimental resolution. This is also reflected in the actual values of emittance (rms) and Twiss parameters given in Tab. 1. Including the almost Gaussian shape of the energy projection this is a clear hint that a direct measurement is not capable of reconstructing the energy spread with the required resolution.

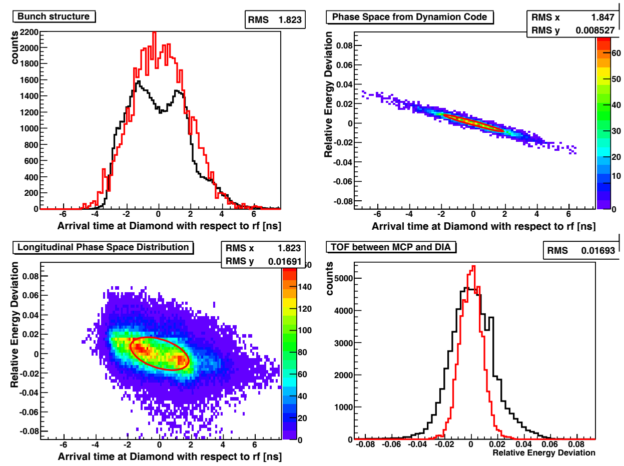

Figure 3: High current data recorded at HIPPI [2] '08 campaign - Ar^{10+} 6.5 mA. Histograms in black show projected measured data whereas red histograms show the projected Dynamion simulation.

Table 1: Direct Measurement vs. Dynamion code (Fig. 3)

Fig. 3		**Measurement**	**Dynamion**
ε_{rms}	$[(keV/u)\,ns]$	0.03	0.004
α		0.5	3.9
β	$[ns/(kev/u)]$	200	862
γ	$[(keV/u)/ns]$	0.01	0.02
$Covar.$	$[(keV/u)\,ns]$	-0.014	-0.015
ΔE_{rms}	$[keV/u]$	24	12
ΔL^*_{rms}	$[ns]$	1.8	1.8

* Bunch length has been used as constraint in simulation.

TIMING REQUIREMENTS

To get a better understanding on the very high timing requirements it is useful to have a look at the expected energy width of an optimized beam at Alvarez entrance. ΔE_{rms} is expected to be around $1\%\langle E \rangle$ and thus

$$\Delta E_{rms}^{expected} \approx 14\ keV/u,$$

which corresponds to a difference in TOF of only about 240 ps at the given drift length of 80 cm.

Uncertainties within the measurement can be classified into dissipative effects and the plain net timing resolution of the setup. Dissipative effects due to straggling occurring in both foils have been estimated using SRIM. The energy spread for a monochromatic ensemble of incidenting particles is calculated to be about $1.7\ keV/u$ for the different species of ions, Ar, Ta and U at the first foil (Ta) of 723 Å thickness and about $0.6\ keV/u$ at the second foil (Al) of 334 Å thickness. As those affect the real physical phase space the corresponding relative error does not depend on the drift length.

On the other hand the timing resolution is a critical limitation which depends on several contributions from the electronics and detector setup. An input jitter of $35\ ps$ has to be considered for each channel of the TDC. Varying signal shapes of MCP pulses do not allow for a better estimation of timing performance than at least $100\ ps$. Also discrimination of diamond pulses show a jitter of at least $50\ ps$. Additionally, as the MCP can not be mounted orthogonal to the beam axis, the foil is adjusted with an angle of $37.5°$ with respect to the particle trajectory. This implies an uncertainty of the drift length that can be estimated from the mean drift length and diamond radius to about $\Delta t^{rms}_{foil} \approx 24\ ps$. As there is no way of calibrating the device it is difficult to state quantitative error values especially for discrimination behaviour of the given signal shapes. Still, it is apparent from all recorded data sets that the device has a limiting energy resolution, and thus the inability to provide a direct measurement of the energy deviation.

PRELIMINIARY POST-PROCESSING

Resolution deficiencies can be treated numerically to some extend. If the response function of the setup is well known deconvolution can improve the interpretation of the recorded data. However, the process of deconvolution is very sensitive to noise which might be a limit of the present setup due to the low event rate. In Fig. 4 deconvolution

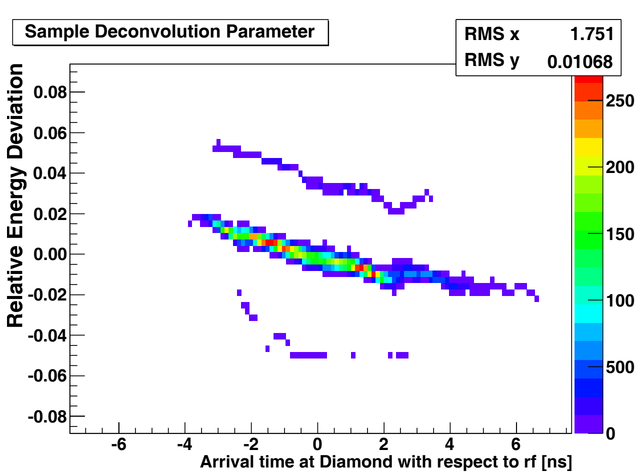

Figure 4: Preliminary post-processing using *Gold Deconvolution* as implemented in *ROOT*. Apart from the suppressed artefacts the resulting distribution tends towards the expected phase space as given in Fig. 3.

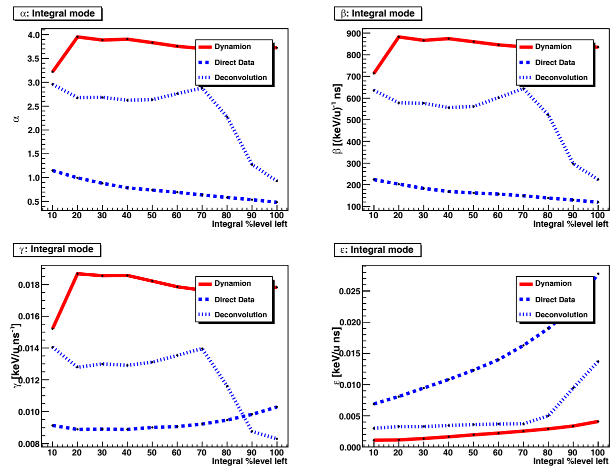

Figure 5: Comparison of *measured*, *deconvoluted* and *Dynamion* data. Integral cutoffs are evaluated by homogeneous removing of events ending on a certain fraction left.

has been applied to each vertical energy slice separately using the *TSpectrum class* implemented in *ROOT* for the data represented above in Fig. 3. The response function is chosen to be of Gaussian shape with an rms width of $1.25\%\langle E\rangle$. The original data has been processed with 100 iterations and 10 repetitions with a boost parameter of 1. To stress the fact of preliminary work these values should be considered of arbitrary character and do not represent a consistent procedure for now. A comparison of the data and simulation is given in Fig. 5 for different integral cutoff levels.

CONCLUSION & OUTLOOK

A novel type of device for measurement of the longitudinal phase space based on TOF using particle detectors has been presented. The high timing requirements for the direct measurement of the energy can not be matched with the resolution achievable at the given drift length. Although a direct measurement is out of scope concerning the full longitudinal phase space, direct bunch length measurements have proven trustworthy as the timing requirements are significantly lower with typical bunch lengths starting at $2ns$. First attempts have been made to use post-processing techniques on the degree of freedom connected to the energy of the particles. Current efforts focus on finding a consistent method to apply deconvolution on a wide scale of recorded data.

REFERENCES

[1] P. Forck et al. "Measurement of the six Dimensional Phase Space at the New GSI High Current Linac", LINAC 2000, Monterey

[2] L. Groening et al. Phys. Rev. Lett. **89**, 094201 (2008).

[3] `http://www.gsi.de/informationen/tt/Double-Threshold-1_e.html`