A NOVEL DEVICE FOR NON-INTERSECTING BUNCH SHAPE MEASUREMENT AT THE HIGH CURRENT GSI-LINAC

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Abstract

For bunch structure determination in the range of 0.1 to 5 ns a novel device has been realized at the GSI heavy ion LINAC. It uses the time spectrum of secondary electrons created by residual gas interaction. Those electrons are accelerated by an electric field of 420 V/mm toward an electro-static energy analyzer. This is used to restrict the effective source region. The time spectrum is transformed into a spatial separation by an rf-deflector driven by the main acceleration frequency (36 or 108 MHz). Single electron detection is performed by a multi-channel plate equipped with a phosphor screen and observed by a digital CCD camera. The achievable time resolution is 50 ps, corresponding to 2^0 of the 108 MHz acceleration frequency.

DETECTOR TECHNOLOGIES

The determination of the longitudinal density distribution of a bunched beam is an important issue because it is required for an optimal matching between different LINAC-modules as well as for the comparison with numerical calculations also taking space charge effects into account. The bunch structure cannot be determined by capacitive pick-ups due to the non-relativistic beam velocities ($\beta < 20\%$ at the GSI-LINAC) causing a faster propagation of the electric field of the bunches. At most LINACs the bunch structure is determined by secondary electrons emitted from a wire crossing the beam [1, 2]. The wire is biased with about -10 kV to pull the secondary electrons toward a slit outside the beam path. An rf-deflector follows, where the electrons are modulated in transverse direction by an electric rf-field. The deflection angle depends on their relative phases, i.e. the device transforms the time information into a spatial difference.

For the high current beam operation at GSI with heavy ions and currents up to 20 mA [3], the beam power is sufficient to melt intersecting materials. The described principle is adapted to a non-intersecting device by performing the time spectroscopy of secondary electrons created by atomic collisions between beam ions and residual gas molecules. The electrons are accelerated by a homogeneous electrical field formed by electrodes outside of the beam pass, as usually used for residual gas profile monitors. To restrict the source region for the secondary electrons, an aperture system and an electro-static energy analyzer is used. The time-to-spatial transformation is performed with the standard type rf-deflector developed at INR (Moscow) [2].

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MONITOR HARDWARE

At the detector location, the beam passes a static electric field region generated by a 160×60 mm^2 electrode biased up to -30 kV, see Fig. 1. With the help of field forming strips, a homogeneous field of 420 V/mm perpendicular to the beam direction guides the secondary electrons toward a grounded plate with a horizontal slit of 1.5 mm in beam direction. To shorten the source length Δz in beam direction and the corresponding divergence of the secondary electron beam, two apertures with a distance of 70 mm are used. Their opening can be remotely varied between 0.1 and 2 mm by dc-motors. The second aperture serves as entrance slit of a 90^0 cylindrical electro-static energy analyzer with a bending radius of $\rho_0 = 30$ mm. The nominal voltages are ± 5.5 kV for the opposite cylinder segments. Two similar devices are installed to place the electron detector perpendicular to the beam pipe. A third aperture is located 10 mm downstream from the second cylinder edge to enable a point-to-point focusing from the entrance- to the exit-slit [4]. Using ± 0.25 mm opening for aperture 1 and 2 and ± 0.5 mm for aperture 3, the vertical source prolongation is restricted to about $\Delta y = \pm 0.2$ mm, i.e. comparable to the wire thickness in the standard method [1].

After a drift of 90 mm the time information is transferred into spatial differences by the rf-deflector synchro-

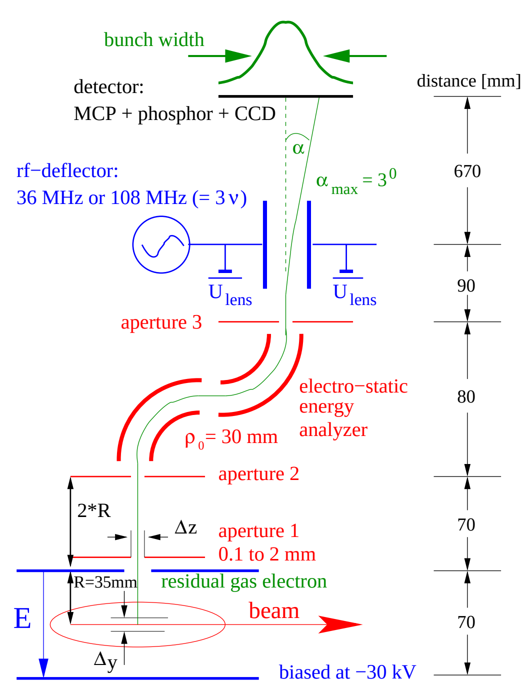

Figure 1: *Schematic sketch of the bunch shape monitor.*

nized with the LINAC rf. Two types of rf-deflectors are available, one running at the base-frequency of 36 MHz for the measurement of long bunches and one for short bunches at the third harmonics at 108 MHz. The deflectors are built as 800 mm long parallel-wire $\lambda/4$-resonators [2] having a quality factor of $Q_0 = 290$ and $Q_0 = 370$ for the 36 and 108 MHz device, respectively. The 108 MHz type has straight parallel-wires, while spiraled wires are used for the 36 MHz device. The maximum rf-power fed into the resonator is 100 W and 30 W for the 36 MHz and 108 MHz, respectively. A pulse length of 6 ms is sufficiently longer than the maximum macro beam pulse. After this transverse deflection and an additional flight length of 670 mm the single electrons are detected by a Ø 70 mm Chevron MCP (Hamamatsu F2226-24P) equipped with a P20 phosphor screen. The light spots are read out with a 12 bit digital CCD camera (PCO SensiCam, 480×640 pixel VGA-resolution, fiber optic link for digital data communication).

To illuminate the full MCP the rf-power of the rf-deflector can be varied. Therefore, quite different bunch lengths can be measured. A calibration of the bunch center position at the MCP with respect to the rf-phase is required to achieve an absolute time (or phase) scale. An accuracy of $\sim 0.5^0$ in rf-phase is reached using a precise digital rf-phase shifter. The rf-deflector also serves as an electro-static lens by applying a common voltage of typically $U_{lens} = -3.5$ kV to both parallel wires[1]. The image of the electron distribution without applying rf to the deflector is $\sigma \sim 4$ pixels (depending on the aperture opening), which is a tolerable resolution limit as typical images of the bunch can have a width of $\sigma \sim 100$ pixels.

MEASUREMENTS

Systematic test measurements were performed at 11.4 MeV/u for several ion beams. A typical raw image of the bunch as seen by the CCD camera is shown in Fig. 2. The deflection with a frequency of 108 MHz is displayed horizontally. The projection of the light intensity on this axis gives the bunch shape. This measurement proves the general functionality of this novel device, where short bunches of $\sigma = 125$ ps had been monitored. It is required to subtract a homogeneous distributed background. This is probably due to x-rays from secondary electrons accelerated by the electric field and hitting the stainless steel plate of the electric field box. A 5 mm thick steel shielding behind the energy analyzer will be installed in the near future to absorb these x-rays (maximum energy 30 keV), thus leading to a strong background reduction by a factor of at least 100. A nearly background-free measurement is expected, which will allow single macro-pulse monitoring. The displayed measurement had been performed with a low current 60 μA Au^{25+} beam. If the amount of secondary electrons does not result in a sufficient statistic, the vacuum pressure can be raised by a regulated gas inlet system. It has been proved, that a local pressure bump up to 10^{-4} mbar

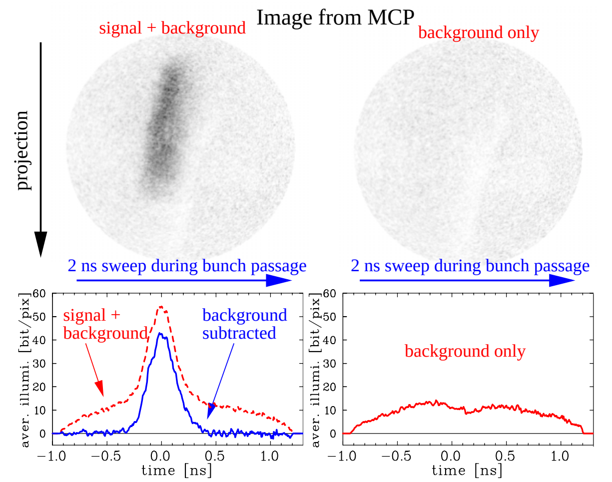

Figure 2: *Typical image (inverted color) from the MCP for a 60 μA Au^{25+} beam averaged over 16 macro-pulses with 1 ms duration and a vacuum pressure of $6 \cdot 10^{-5}$ mbar. 8 W had been fed to the 108 MHz rf-deflector. The background is displayed right.*

in the transfer lines does not influence the beam properties. Due to the statistical nature, averaging also improves the signal-to-noise ratio leading to a large dynamic range.

By varying the voltage amplitude of a buncher cavity and measuring the bunch width, the longitudinal emittance can be calculated by fitting a parabola through the square of the bunch width. This is shown in Fig. 3. For a high current, 2 mA Ni^{14+} beam only 4 macro-pulses of 0.2 ms duration were averaged, as shown in Fig. 3. Due to the nature of the fitting procedure, the error is relatively large, but it offers a simple method of emittance estimation.

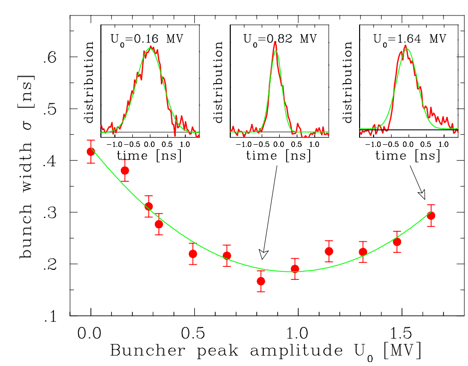

Figure 3: *Measurement of the bunch width (one standard deviation) as a function of the buncher voltage 31 m upstream to the detector performed with a 2 mA Ni^{14+} beam.*

NUMERICAL CALCULATIONS IN THE PRESENCE OF SPACE CHARGE

In addition to the external homogeneous electric field the secondary electrons are influenced by the space charge field of the bunches. A numerical analysis is required to estimate the beam current and bunch length, where the electron trajectories are deformed significantly, resulting in a misleading signal reading.

As a model for the bunches, a parabolic charge distribution was used. For an equal transverse, but arbitrary

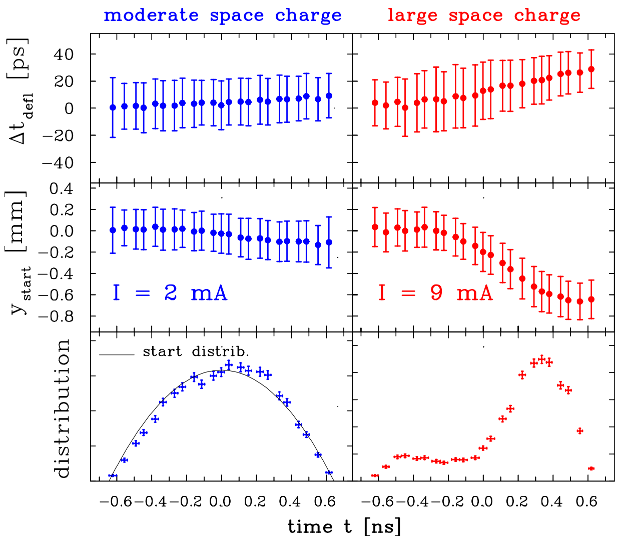

Figure 4: *Simulation for a parabolic bunch shape at 11.4 MeV/u, 36 MHz repetition rate and a transverse parabolic beam size of* ± 5 *mm root points. The left column shows the simulation for 2 mA current and the right column for 9 mA.* Top: *arrival time* Δt_{defl} *at the rf-deflector with respect to the reference particle.* Middle: *vertical start co-ordinate* y_{start}*; the error bars are the standard deviation of the ensemble.* Bottom: *Number of detected electrons; vertical error bars given by the square root of the number, horizontal error bars are the ensemble standard deviation of the arrival time.*

longitudinal prolongation, the electric field of the moving bunches can be given analytically [5]. Using a Runge-Kutta scheme the secondary electrons are tracked with a time resolution of 0.3 ps per step toward aperture 1 in Fig. 1. From thereon linear optics are adequate for the action of the electro-static analyzer and related drift spaces. The three dimensional start co-ordinates and velocities for the secondary electrons are chosen by a Monte-Carlo simulation satisfying the given distribution function. For the initial velocities a realistic distribution function for the 'δ-electrons' [6] was used with a maximal electron energy of 100 eV. Varying this cut-off energy has only a small influence on the signal shape, because most electrons are emitted with lower energies.

We discuss the essential features for the case of the reported measurements shown in Fig. 3 having a beam current of 2 mA and a bunch length of $\sigma = 0.2$ ns. The functionality for the device can be characterized by three plots, as shown in Fig. 4. First is the time resolution, i.e. the spread of the arrival times as a function of time during the bunch passage (Fig. 4 top left). For the medium current range of 2 mA this time spread remains ± 20 ps without significant shifts along the bunch. The second quantity is the spread of the initial position along the bunch (Fig. 4 middle left). For the 2 mA case the detected particles are created within ± 0.2 mm, with a slight decrease by 0.2 mm at the bunch head. The third quantity is the number of detected electrons as a function of bunch position, which correspond directly to experimentally determined signal strength (Fig. 4 bottom left). There is only a small deformation around the bunch center, which is below the required signal accuracy. This proves the right signal reading and resolution for those parameters.

With a current increased to 9 mA the time resolution is slightly worse: Secondary electrons created by the bunch head arrive ~ 30 ps earlier (Fig. 4 top right). Those electrons are created ~ 0.6 mm below the bunch center (Fig. 4 middle right). This is tolerable due to the transverse beam width of $\sigma = 2.3$ mm and the lack of a vertical-longitudinal coupling. However, the number of detected electrons as a function of the bunch position shows a maximum at the bunch head (Fig. 4 bottom right). This can be qualitatively explained by the electric field at the bunch head, which pulls the secondary electrons toward the bunch center. These electrons are influenced during their full passage of ~ 1.1 ns toward aperture 1. For the secondary electrons from the bunch tail, this strong force acts in a shorter time because the bunch departs from the active detector volume. This limits the applicability of the present device in case of very short and intense bunches.

CONCLUSION

A novel, non-intersecting device for the bunch structure determination has been proposed and successfully tested. It can be used in a wide current range and offers a direct determination of parameters that are difficult to measure. For high currents and moderate bunch-length in the ns range (i.e. the high current operation parameters at GSI), the bunch structure is reproduced faultlessly. For very short and intense bunches having a large space charge field, the application in the present form is limited. It might be necessary to guide the secondary electrons from their generation location toward aperture 1 by a magnetic field of ~ 0.1 T parallel to the electric field, as normally used for residual gas profile monitors [7].

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