OPTIMIZATION OF BEAM INDUCED FLUORESCENCE MONITORS FOR PROFILE MEASUREMENTS OF HIGH CURRENT HEAVY ION BEAMS AT GSI

C. Andre, P. Forck, R. Haseitl, A. Reiter, R. Singh, B. Walasek-Hoehne,
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany

Abstract

To cope with the demands of the Facility for Antiproton and Ion Research (FAIR) for high current operation at the GSI Heavy Ion Linear Accelerator UNILAC non intercepting methods for transverse beam profile measurement are required. In addition to intercepting diagnostics like Secondary Electron Emission Grid (SEM-Grid) or scintillating screens, the Beam Induced Fluorescence (BIF) Monitor, an optical measurement device based on the observation of fluorescent light emitted by excited nitrogen molecules, was brought to routine operation. Starting with the first installations in 2008 and consequent improvements, successively six monitors were set up in the UNILAC and in the transfer line (TK) towards the synchrotron SIS18. BIF is used as a standard diagnostic tool to observe the ion beam at kinetic energies between 1.4 and 11.4 MeV/u. Beside the standard operation mode where the gas pressure is varied, further detailed investigations were conducted. The BIF setups were tested with various beam parameters. Different settings of camera, optics and image intensification were applied to improve the image quality for data analysis. In parallel, the light yield from different setups was compared for various ions, charge states, beam energies and particle numbers.

INSTALLATIONS

Along GSI linear accelerator UNILAC and transfer line, six BIF monitors are installed. Each monitor consists of two perpendicularly mounted image intensified camera systems to measure transversal beam profiles in horizontal and vertical plane simultaneously (see Figure 1 and Table 1). The monitors are placed to observe changes of the beam due to stripping or acceleration. Profiles and positions of a single linac pulse can be observed at all positions without beam distortions.

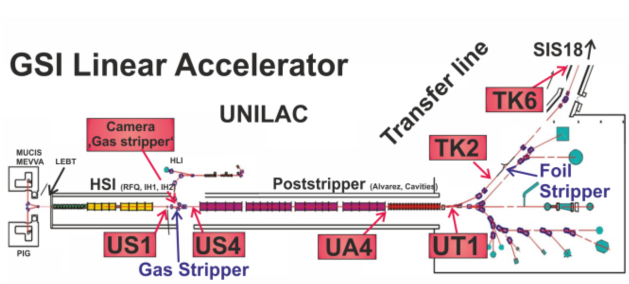

Figure 1: Locations of BIF monitors along GSI Linear Accelerator.

In addition, a regular CCD camera observes beam induced fluorescence at the gas stripper to control the gas flux. Here, different charge states of the same beam can be observed within one image.

Table 1: BIF Installations and Typical Beam Parameters

BIF		US1	US4	UA4	UT1	TK2	TK6
CCD	**H**	T	R	T	R	T	T
coupling	**V**	T	R	T	R	T	R
Energy [MeV/u]		1.4	1.4	11.4	11.4	11.4	11.4
Typical charge states :							
Argon		1+	11+	11+	11+	11+	18+
Nickel		2+	14+	14+	14+	14+	26+
Tantalum		4+	24+	24+	24+	24+	62+
Uranium		4+	28+	28+	28+	28+	73+

DETECTOR SETUP

The BIF principle and the detailed setup (hardware, optics, readout and control) of the system is described in [1]. To observe the fluorescence of the ion beam interaction with the nitrogen gas molecules at lowest gas pressures, image intensified camera systems (ICCD) are required, preferably with a 2-stage multichannel plate (MCP) to enable single photon counting. ProxiVision® developed two custom designed camera types; a fiber-taper coupled CCD (T) where the CCD chip is glued to the taper and a relay-lens coupled CCD (R) with c-mount standard (Figure 2, Table 1).

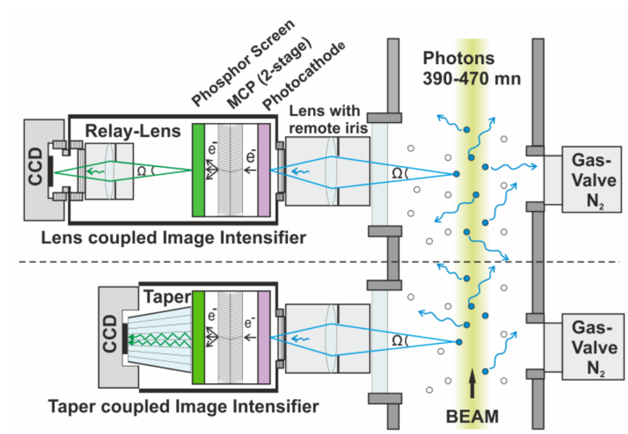

Figure 2: Types of Image Intensified Camera Systems.

Copyright © 2014 CC-BY-3.0 and by the respective authors

Fiber-tapered cameras intrinsically offer a higher light yield due to the higher coupling efficiency between phosphor and CCD chip, whereas relay-lens coupled systems are easier for maintenance e.g. malfunctioning CCD cameras screwed on the c-mount can easily be replaced without removing the image intensifier from the beam line installation. Thus, the relay-lens coupled camera systems are preferred for permanent installations in the future. Currently, both types of image intensifier systems are set up in the UNILAC (see Table 1).

Prior to installation, each camera lens was separately calibrated and the light transmission can be chosen relative to the fully opened iris (100 %, f-stop 1.4).

All images of the CCD cameras are recorded in 8 bit.

SIGNAL EVALUATION

Operational parameters for BIF to gain signal strength and quality are the N_2 gas pressure, the iris opening and the MCP high voltage. By setting MCP and iris in a proper way, both systems can be used for profile measurements in

- Event counting (EC) mode
  Requires a high intensifier gain for efficient single photon detection and relies on bright, well separated event signatures.
  The captured image, after defining a threshold, is converted to a binary image and checked for connected components of minimum 2 neighbouring pixels, so called events. Each event has vertex (x/y), where profiles are projections of the vertices in the vertical plane. The total light yield is the number of counted events N_{EC} in the image.
- Charge collection (CC) mode
  The intensifier gain is adjusted to avoid camera saturation at the expense of some detection efficiency. Here, the overlap of detected events is not a problem as long as no saturation occurs.
  A background is calculated by the outer region of the image and subtracted from each pixel. The total light yield N_{CC} is obtained by integration over the CCD matrix after background subtraction. Profiles are projections of the matrix in the vertical plane.

The two different modes ideally demand for specific settings of the complete camera system. Figure 3 shows typical images for both analysis modes.

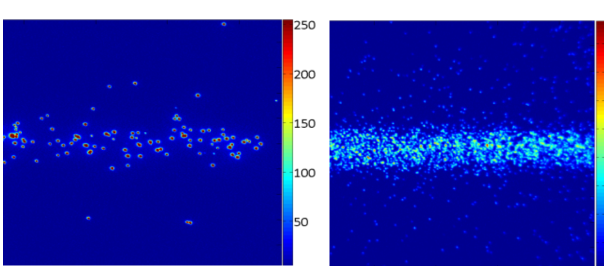

Figure 3: Typical images for counting mode (left) and for charge collection (right).

For a comparison in Figure 4, both ways of data analysis were performed for images with different iris settings under constant beam conditions and camera settings. For the CC mode, the maximum grayvalues were ~120, thus saturation of pixels was excluded. For the EC mode, the events were clearly separated for counting for an almost closed iris and the threshold was manually adjusted for each measurement. The resulting curves normalise to the lowest iris setting of the event counts.

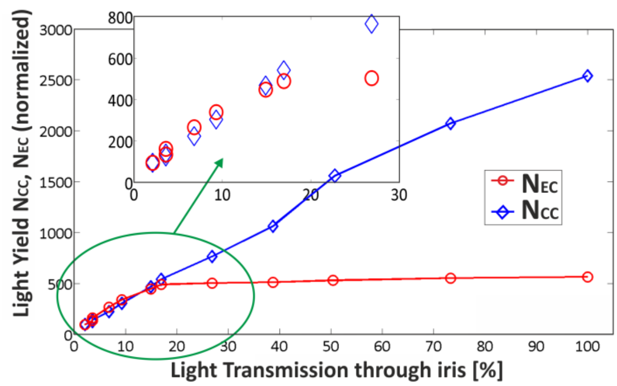

Figure 4: Comparison of event counting mode and charge collection mode for varied iris opening. Beam parameters: US4, N^{4+} beam, 1.4 MeV/u, $8.4{\cdot}10^{11}$ ppp, $5{\cdot}10^{-6}$ mbar N_2 pressure.

The obtained results (Figure 4) clearly show that the dynamic range of the N_{CC} mode is a factor of 5 larger than the N_{EC} mode. For these images and beam settings, the events start to overlap at ~200 events in an image.

Figure 5 shows an image with defined ROI, where consistent projections in both modes were obtained. For the charge collection mode, a background was subtracted and no pixels were saturated. Within the ROI, the N_{EC} was ~130.

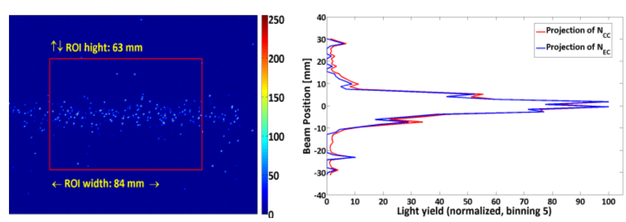

Figure 5: Raw image and projections in the CC and EC-mode, both binned by a factor of 5. Beam parameters: TK6, Ta^{24+} beam, 11.4 MeV/u, $3.8{\cdot}10^{10}$ ppp, $5{\cdot}10^{-6}$ mbar N_2 pressure.

For images with fewer events, integration over several pulses is possible to obtain a reasonable profile. Especially to depict the beam position of a single linac pulse from images with low signal, the charge collection mode is more sensitive. Figure 6 shows a projection of few, slight grey events in the CC mode (pixel value on events ~50, subtracted background and binned by a factor of 5) and the corresponding profile of a SEM-Grid. Both systems are in good agreement.

ISBN 978-3-95450-141-0

Copyright © 2014 CC-BY-3.0 and by the respective authors

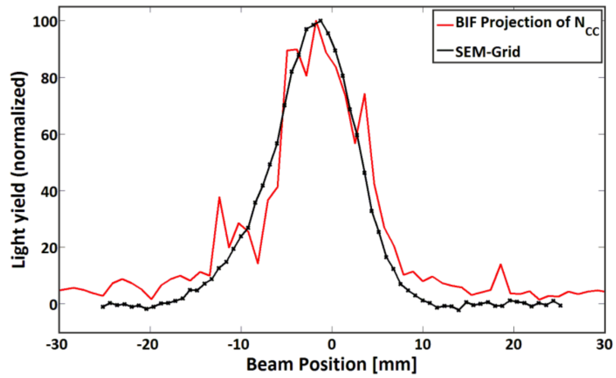

Figure 6: Comparison of the beam position at TK2, measured by BIF and a SEM-Grid. Beam parameters: U^{39+} beam, 11.4 MeV/u, $3\cdot10^{10}$ ppp, $5\cdot10^{-6}$ mbar N_2 pressure.

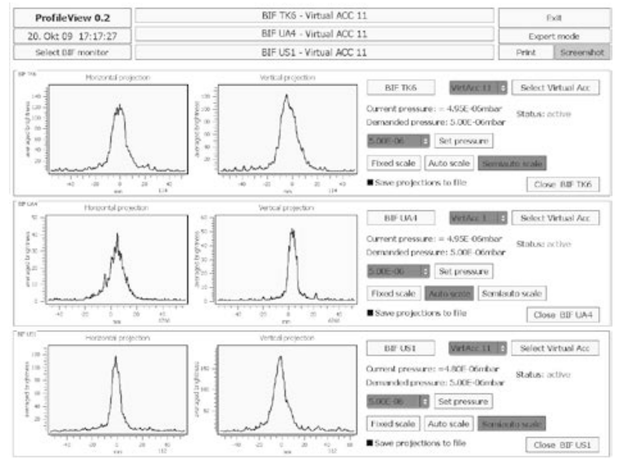

Figure 7: GUI of Profile View for operating.

BIF IN OPERATION

For the usage of BIF as a beam diagnostic monitor, a wide range of ions, particle numbers and charge states as well as different beam positions have to be covered. This demands for a high dynamic of the detector and robust and reliable analysis of the image data. Where the event counting mode strongly depends on user defined parameters, e.g. the threshold has to be set case by case, the charge collection mode uses fixed settings for all parameters of the CCD and image intensifier. For each individual detector, appropriate settings of MCP high voltage, iris opening and CCD gain were determined by tests to achieve small events with grayvalues around 100 and saved in an initialization file. Hence, the charge collecting mode is more suitable and preferred for standard operation (see Figure 4).

The software 'Profile View' [2] that is used by the operating crew for beam position and profile measurements offers a 'User Mode', where the N_2 gas pressure as the operational parameter can be varied stepwise up to a maximum of $5\cdot10^{-6}$ mbar. For the user mode, all other settings are loaded from the initialization file. The Profile View GUI (Figure 7) shows the horizontal and vertical beam positions for three BIF detectors simultaneously. To determine the beam position and profile width, a projection of the raw image data in the CC-mode without background subtraction is sufficient. For a better profile appearance, an additional smoothing is provided. During beam alignment with BIF, ongoing experiments can continue without any disturbance.

An additional 'Expert Mode' enables to view and save the raw images. Here, further settings for gas pressure, MCP high voltage and the iris opening can be applied. Beside this, the expert has remote access to all parameters of the CCD (gain, integration time …) and the timing of all the devices. The 'Expert Mode' is mainly used for experiments, system calibration and diagnostic inspection, if unexpected signals occur and a 2-dimensional view of the beam trajectory is necessary.

COMPARISON OF NORMALIZED SIGNALS

BIF data was recorded over years during routine operation, by using the given beam parameters and settings. Unfortunately, dedicated UNILAC beam times for BIF with specified beam conditions are quiet rare. During most data acquisitions, only the settings of the detector itself could be varied for different studies, e.g. the behaviour of the gas pressure, of the iris opening or the MCP high voltage. These experiments and results can be found in [3], [4].

Here, the recorded data of multiple beam times at all BIF installations positions (see Table 1) with varying camera settings, N_2 pressure settings and beam parameters (ions, charge states, current) were compared, after normalization based on the Bethe-Bloch scaling [5]. Though optics, mechanics and hardware of all setups was kept identical, the characteristics of the Image Intensified Camera Systems varies according to the type of photocathode, their quantum efficiency, the overall gain of the MCPs and the type of coupling (see Figure 2). Thus, the event signature of all camera systems slightly deviates. Hence, for this comparison, preferably images with clearly separated events were chosen to be analysed in the EC-mode. Counting here is an advantage, because if the MCP high voltage was set to a reasonable value and the events appear clearly and separated on the CCD chip, one can assume an efficiency of ~1 for each electron reaching the the MCP and triggers an avalange, independently of the exact MCP voltage, the CCD gain and the type of coupling. For a relative comparison of the different measurements, the counted events N_{EC} of each image have to be normalized as follows.

The number of expected events N_{EC}, as described in [5-7] is defined as

$$N_{EC} = N_{Ions} \cdot \rho \cdot x \cdot \frac{N_A}{A} \cdot \sigma \cdot \varepsilon_{Iris} \cdot \varepsilon_{Detector} \qquad (1)$$

$$\sigma(E) \propto {}^{dE_P}\!/_{dx}\,(E) \cdot q^2 \qquad (2)$$

Copyright © 2014 CC-BY-3.0 and by the respective authors

Where

N_{Ions} number of incident beam ions (ppp)
ρ mass density of the target
x observation length in beam direction; here fixed by a constant image ROI
N_A Avogadro number
A mass number of the target
σ cross section
ε_{Iris} iris opening (resp. light transmission)
$\varepsilon_{Detector}$ a global constant for each detector, including the solid angle for an open iris, the efficiencies of the flange, the iris, the photocathode and the penetration into the multichannel plate
E_P kinetic proton energy
$^{dE_P}/_{dx}(E)$ differential proton energy loss for energy E
q charge state of the ion

For a relative comparison of the measurements, constant values of Equation (1) for x, N_A/A and $\varepsilon_{Detector}$ can be neglected.

$$N_{EC} \propto N_{Ions} \cdot \rho \cdot {}^{dE_P}/_{dx}(E) \cdot q^2 \cdot \varepsilon_{Iris} \qquad (3)$$

The following parameters are given for each measurement and taken into account for normalization:

N_{Ions} known for the beam pulse
ρ calculated from the nitrogen gas pressure
ε_{Iris} iris opening of the calibrated lens

For the UNILAC energy of 11.4 MeV/u with a constant $^{dE_P}/_{dx}$ [8], the number of events is proportional to the q^2.

$$N_{EC} \propto q^2 \qquad (4)$$

Figure 8 shows the normalized number of events N_{EC} for different detectors and ions. Each data point is the average number of counted events over 100-150 images with corresponding standard deviation, where each set of images was checked for consistency by testing different threshold settings. The data was normalized in respect to the gas pressure, the iris opening, the particle number, the differential energy loss and to the square of the ion charge state.

After normalization, N_{EC} data scatter within a factor of three between the measurements of Ar^{10+} to Ta^{62+} (Figure 8). Since the q^2 ratio between these charges would be a factor of ~40, a factor of three here seems reasonable. The data were taken on different detectors in parallel to standard operation and the detector settings were not optimized for EC mode. Beside this, the pulse-to-pulse beam current was not recorded in parallel, so an average value for each series of images was taken for the normalization. Also the true gas pressure at different locations can vary, depending on the installation in the chamber. The results presented in Figure 8 acceptably support the q^2 dependency for various ions at the energy of 11.4 MeV/u and show a consistency of the individual detector settings.

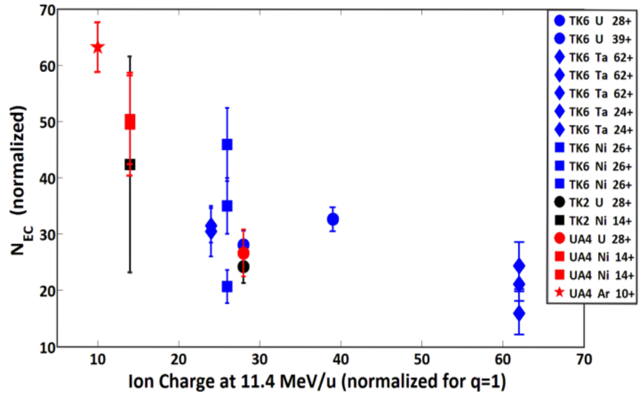

Figure 8: Counted events (data normalized on q=1 and on the particular measurement settings) for various measurements on different BIF installations.

During one dedicated experiment, a direct comparable measurement could be performed with a tantalum beam, once stripped at the stripper foil to Ta^{62+} and unstripped with Ta^{24+}. At the BIF installation TK6 horizontal and vertical images could be taken of both charge states without any changes of the detector settings, gas pressure and so on. All detector characteristics, defined by $\varepsilon_{Detector}$ can be neglected, e.g. the fact, that the horizontal camera system is a fiber-tapered one, whereas the vertical camera system is relay-coupled. To use the same images for both modes of data analysis, the camera parameters were chosen carefully to have maximum 100 events and grayvalues < 150 in an image. By this, beside the event counting mode, also the total light yield in the charge collecting mode could be compared for both tantalum charge states (see Figure 9).

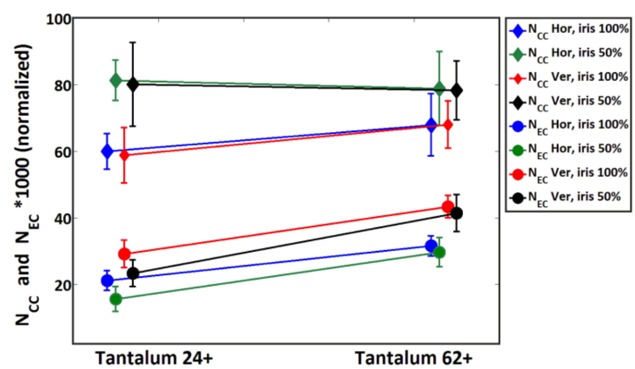

Figure 9: Number of collected charges and counted events (normalized on q=1 and on the particular measurement settings) for Ta^{24+} and Ta^{62+} beam in TK6. The lines present corresponding data sets.

Figure 9 strongly supports the q^2 dependency for the CC and EC mode. The deviation of a few percent is acceptable and could derive from the iris calibration that also shows a hysteresis curve or be due to the usage of an average current value for one data set.

Copyright © 2014 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-141-0

CONCLUSION

BIF detectors are non-invasive and able to measure the beam position and achieve transversal beam profiles at 6 dedicated positions in the UNILAC within one beam pulse. A systematic check of the alignment over the whole linac and transfer line can be done with the BIF monitors.

The installed BIF detectors offer a reliable and robust measurement of beam position and transversal profiles for high current beams. For operation, the data analysis is done in the charge collecting mode as a projection of the raw image, which offers a high dynamic and sufficient accuracy, even without background subtraction. Hence, the event counting mode seems less practical and more complex for daily operation, because the quality of the counting strongly depends on the settings of the threshold and on overlapping events.

For a relative comparison between different BIF systems with deviating characteristics of the image intensified camera systems, the event counting mode turned out to be more appropriate. Settings of MCP voltage or camera gain can be neglected if clear bright events on the CCD are achieved. At the UNILAC energy of 11.4 MeV/u, the q^2 dependency of normalized N_{EC} signals of multiple different measurements and detectors could be shown.

A further dedicated experiment at 11.4 MeV/u of a tantalum beam at two different charge states strongly supports the q^2 dependency on the basis of the applied normalization. Similar results that also support the q^2 dependency were published by T. Tsang [7] for relativistic ions of different charge states.

OUTLOOK

For future installations at GSI linear accelerators and in the High Energy Beam Transport (HEBT) lines of FAIR, numerous non intercepting profile measurements, e.g. BIF are demanded. For permanent installations, the relay-coupled image intensified cameras are preferred, due to the better maintenance. Beside the lower overall intensity on the CCD chip which can be compensated by higher MCP voltages, the appearance of the events is smaller with a better distribution.

The normalization is a first step for automized detector setting generation for multiple beam production with shot-by-shot changes of ion species. This will get more important for future installations in linear accelerators and the HEBT of FAIR.

ACKNOWLEDGMENT

Thanks to all my colleagues at GSI for help with the BIF setups, data acquisition and analysis.

REFERENCES

[1] C. Andre et al., “Beam induced Fluorescence (BIF) Monitors as a Standard Operating Tool”, DIPAC 2011, Hamburg, Germany, p. 185

[2] R. Haseitl et al., “ProfileView – A Data Acquisition System for Beam Induced Fluorescence Monitors”, DIPAC 2009, Basel, May 2009, p. 134

[3] F. Becker et al., "Beam Induced Fluorescence (BIF) Monitor for Transverse Profile Determination of 5 to 750 MeV/u Heavy Ion Beams ", DIPAC 2007, Venice, May 2007, p. 33

[4] F. Becker, “Non-destructive Profile Measurement of intense Ion Beams”, PhD-thesis, Darmstadt, 2009

[5] A. Variola et al., “Characterization of a Non-destructive Beam Profile Monitor using Luminescent Emission”, Physical Review Special Topics - Accelerators and Beams 10 (2007), August, Nr. 122801, S. 1–14

[6] D. Sober et al., “An Introduction to Cross Section”, Physics 537/635, January 2005 (rev. 2007)

[7] T. Tsang et al., “Residual Gas Fluorescence Monitor for Relativistic Heavy Ions at RHIC”, Physical Review Special Topics - Accelerators and Beams 16 (2013), Nr. 102802, S. 1-7

[8] http://www.srim.org

Copyright © 2014 CC-BY-3.0 and by the respective authors