PROFILE MEASUREMENT BY BEAM INDUCED FLUORESCENCE FOR 60 TO 750 MeV/u HEAVY ION BEAMS

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Abstract

For intense heavy ion beams, as planned for the facility for anti-proton and ion research (FAIR) non-destructive methods for the transverse beam profile determination are required. We experimentally investigated the Beam Induced Fluorescence (BIF) method. Due to atomic collisions with the beam ions, the residual gas N_2 is excited to fluorescence levels. Single photons were detected by a double MCP image intensifier coupled to a digital CCD camera. Our experimental studies (with lower ion currents which are available today) aimed to determine the photon yield and the background contribution for different ion species (Xe, Ta, U) and beam energies from 60 to 750 MeV/u. The measured profiles are in good agreement with other methods.

THE BIF METHOD

At the future heavy ion facility FAIR very intense beams will be transported between several synchrotrons and focused on targets for secondary ion production as well as plasma-physics investigations [1]. For the design-case of $5 \cdot 10^{11}$ Uranium ions in a single pulse, the focused beam will melt any intercepting material. As an alternative to the traditional SEM-Grids, the transverse beam profile in the transport lines could be determined by observation of single fluorescence photons emitted by residual gas molecules. The related device is called **B**eam **I**nduced **F**luorescence (**BIF**) Monitor [2] as schematically shown in Fig. 1. During the last years the BIF method was applied successfully at the GSI heavy ion LINAC for various ion species and energies between 4 and 11.4 MeV/u [3]. Now we have investigated its application for higher energies as extracted from the heavy ion synchrotron SIS18. Beside the signal amplitude, the background contribution is of interest, due to the rising neutron production.

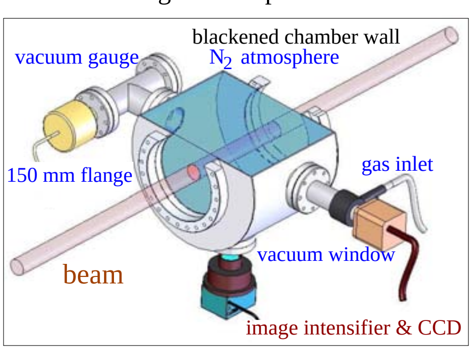

Figure 1: Scheme of a BIF-Monitor.

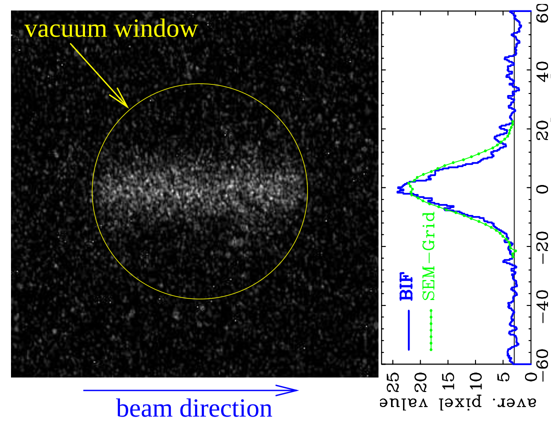

Figure 2: Image from a 1.5 μs long pulse of $2 \cdot 10^9$ Xe^{48+} at 200 MeV/u. The projected horizontal profile is compared to SEM-Grid data. The BIF data were recorded at $1 \cdot 10^{-3}$ mbar and averaged over 20 shots.

When the beam collides with the residual gas molecules, some molecules are ionized and with a certain probability left in an excited state. In a N_2 dominated residual gas composition, a strong fluorescence [4] in the blue wavelength range $390\,\text{nm} < \lambda < 470\,\text{nm}$ and a lifetime of about 60 ns is generated by a transition band to the N_2^+ electronic ground state $(B^2\Sigma_u^+(v') \rightarrow X^2\Sigma_g^+(v'') + \gamma$, for vibrational levels v). 'Single-photon counting' is performed with a commercial image intensifier (Company Proxitronic), equipped with a double Micro-Channel Plate (MCP) for up to 10^6-fold photo-electron amplification. The light from the fast P46 phosphor screen with 300 ns decay time is taper-coupled to a digital CCD camera with a FireWire interface (Basler A311f). The device is mounted at a distance of 20 cm from the beam axis. Observation through a lens of 8 mm focal length with remote-controlled iris leads to a resolution of 377 μm/pixel. A more detailed description can be found in [3, 5]. The setup is installed behind SIS18 at a distance of 2.1 m from the beam dump. It has been tested for Xe, Ta, U ions having energies between 60 and 750 MeV/u in fast and slow extraction-mode. An example of is shown in Fig. 2: The spots within the area of the vacuum window are created by single optical photons, their projection along the beam axis yield the horizontal profile. The good agreement with SEM-Grid measurements proves the applicability. However, the BIF method offers a higher spatial resolution, which can easily be matched to other requirements by the choice of an appropriate lens/taper system. In addition, a BIF Monitor can be realized in a more compact design compared to an Ionization Profile Monitor.

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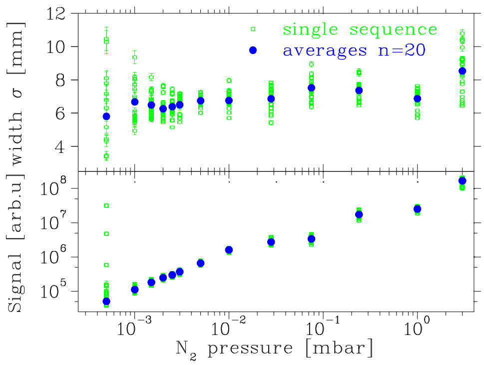

Figure 3: Measured profile width σ and total signal amplitude shown as a function of vacuum pressure, determined with the beam parameters of Fig. 2.

SIGNAL DEPENDENCE ON N_2 PRESSURE

For sufficient signal strength on single shot basis, a relatively large pressure bump of typically 10^{-3} mbar was required for the investigated beam currents. These currents are two to three orders of magnitude lower than expected of FAIR. To legitimate the necessary extrapolation for the FAIR design values, the vacuum pressure was varied via a regulated gas-valve by nearly four orders of magnitude to larger pressures. To compensate for the increasing light intensities, the iris opening was reduced and the MCP-gain was lowered; the recorded profiles were then corrected by the resulting factor. Fig. 3 confirms the pressure independence of the measured profile width σ, while the total signal amplitude increases linearly with the N_2 pressure.

For the quantitative evaluation of the profile width in Fig. 3, two corrections had to be applied: Firstly, the vignetting of the lens system has to be considered, which is particularly important for a short focal length and an open iris. Depending on the profile shape, a correction between 2 to 8 % with respect to the calculated width σ was necessary. Secondly, the fluorescence light reflected at the vacuum chamber leads to a homogeneous distribution with respect to the vacuum window. The projection in beam direction of this round area results in a half-elliptical curve with an integral proportional to the direct fluorescence light. Even though the inner chamber walls had been blackened with vacuum suitable graphite lacquer (graphite grains solved in isopropanol), about 20 % of the acquired light intensity is originated by reflected photons. Subtracting the normalized half-ellipse, the shoulders of the raw profile data could be removed independently of the signal amplitude and shape.

For pressures $p > 1$ mbar, a 2-step excitation process becomes more important with a probability scaling $\propto p^2$. In the first step the ionizing collisions between the beam ions and N_2 cause free electrons. In the second step these electrons can excite N_2 from the ground state $X^1\Sigma_g^+$ to triplet-states leading to fluorescence-light in the near UV (337 nm $< \lambda <$ 358 nm caused by $C^3\Pi_u \rightarrow B^3\Pi_u + \gamma$). As the mean free path of electrons at 1 mbar is about 1 mm, these electrons may travel a certain distance prior to

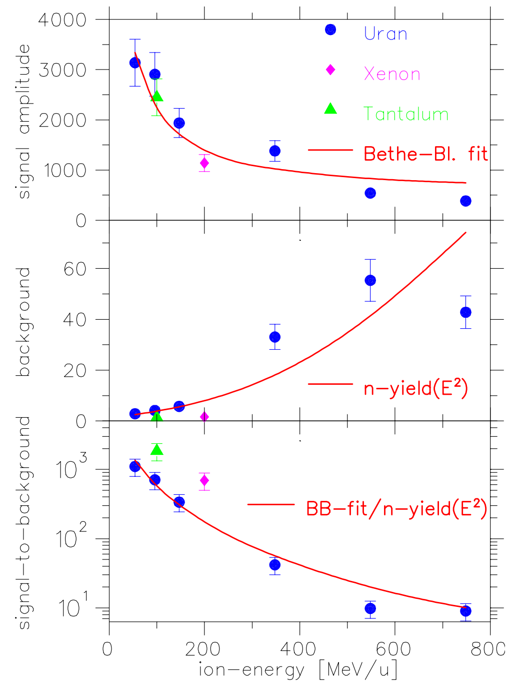

Figure 4: The total signal amplitude (top), background level (middle) and signal-to-background ratio (bottom) as a function of energy for the investigated ions. The signal amplitude for Xe and Ta ere normalized by their charge and mass with respect to U. The background was normalized with respect to the mass only.

the molecular excitation. Therefore the beam-profile can be enlarged. If the UV-light from the 2-step process is suppressed with an optical low-pass filter (GG395) in front of the image intensifier, the measured profile-width is reduced. Even at 2 mbar pressure the contribution is low, as a reduction of only 10% was detected for a beam width $\sigma \sim 8$ mm.

SIGNAL DEPENDENCE ON ENERGY

The BIF method should be applied for ion beam energies from 100 MeV/u up to 10 GeV/u as provided by FAIR. Tests were performed for slowly extracted U^{73+} ions with energies between 60 and 750 MeV/u. The uniformly distributed background was subtracted from the integrated signal and the resulting amplitude is plotted in Fig. 4, top. The energy loss in matter is described by the Bethe-Bloch formula and is characterized by a $\sim q^2/E$ dependence. Because the beam pipe at the location of detection is separated from the transport-lines by a 50 μm stainless steel vacuum window, energy loss $E_{in} - E_{out}$ and energy-dependent electron stripping have to be taken into account. The mean charge states $\overline{q}$ for the accelerated U^{73+} were calculated by the code GLOBAL [6]:

E_{in} [MeV/u]	60	100	150	350	550	750
E_{out} [MeV/u]	52	94	145	346	547	747
Mean charge $\overline{q}$	85.8	88.7	89.7	90.7	90.8	90.9

E_{out} and $\overline{q}^2$ were inserted into the Bethe-Bloch formula

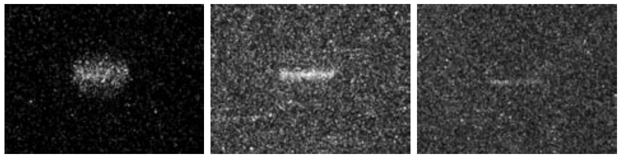

Figure 5: Images from an U beam for different energies and a pressure of $2 \cdot 10^{-3}$ mbar are shown.

and fitted with the parameter a to the fluorescence yield $Y = a\frac{dE}{dx}(E_{ouit}, \overline{q})$, as shown in relative units in Fig. 4, top. The agreement with the measured signal amplitude is quite good, supporting the proportionality between energy loss and fluorescence yield Y. The data for the other investigated ions Xe and Ta were normalized by the corresponding mass and charge ratios and are described by the same scaling law.

BACKGROUND CONTRIBUTION

The most critical issue for the BIF method is the background contribution. As an example, BIF-images for the U beam with three different energies are shown in Fig. 5. The background is uniformly distributed on the image and increases as a function of energy as summarized in Fig. 4, middle. The independence on the iris opening and vacuum pressure judges that the background is not caused by optical photons. Also charged particles can be excluded, due to their limited range in the surrounding material of the image intensifier. In connection with the simulation described below we conclude, that the main source was neutron production in the 2.1 m distant beam-dump. This was also verified by ^{6}Li and ^{7}Li based thermo-luminescence monitors, where ~80 % of the absorbed dose was due to neutrons. About half of them had energies above 20 MeV.

The cross section of neutron production rises approximately proportional to the square of the energy and to the number of nucleons [7]. These neutrons are scattered and slowed down in the surrounding concrete walls. A realistic model of the beam-dump and the cave walls at ~ 2 m distance from the beam pipe was used as input for the Monte-Carlo Transport code PHITS [8]. For the case of the 200 MeV/u Xe beam, flux, energy spectrum and time evolution of the neutrons at the BIF-Monitor location were simulated. The energy spectrum is consistent with the result of the thermo-luminescence monitor. Due to the scattering in the walls, the neutron arrival at the detector is delayed with respect to their generation. The measured count-rate is shown in Fig. 6 and can be approximated by two exponential functions with time constants $\tau_1 = 0.04$ ms and $\tau_2 = 2.3$ ms. It coincides with the measured count rate by a shielded plastic scintillator (decay constant $\tau = 1.7$ ms), which was mainly sensitive to neutrons. The background contribution of the BIF-Monitor showed the same time behavior, as determined for the fast extracted Xe and Ta beams of 1.3 μs duration and a varying exposure time of the image intensifier between 3 μs and 15 ms. For the short exposure time matched to the beam delivery, the background contribution was reduced by a factor ~ 4. This is the reason for the improved signal-to-background ratio for the fast extracted Xe and Ta beams in Fig 4, bottom, compared to the slowly extracted U beam. For slow extraction over several seconds, short gating cannot be applied and thus the background contribution is higher.

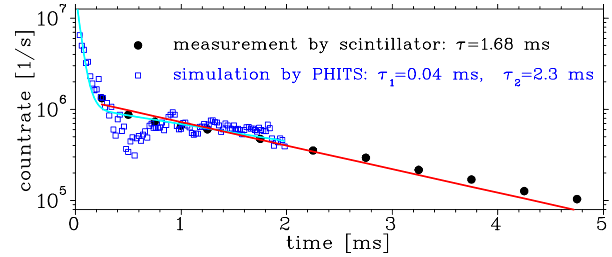

Figure 6: The time evolution of neutron arrival at the BIF-Monitor (simulated by PHITS) compared to the counts recorded by a BC400 plastic scintillator. Due to the count rate limitation of the scintillator, the first part up to ~ 0.3 ms is not measured properly.

CONCLUSION

The BIF method for non-intercepting profile measurements is an alternative even at energies much above the Coulomb-barrier. Compared to an Ionization Profile Monitor it has a shorter insertion length. In particular, this is important for intense beams in the vicinity of targets. In these experiments, diagnostics have to be performed as close as possible to the required small beam focus. A moderate pressure bump should be acceptable there to achieve a sufficient signal amplitude. For background reduction, a careful shielding of the image intensifier against neutrons is required. To enlarge the distance to the beam pipe, a commercially available 'Fibre Optics Image Bundle' might be a solution. The background can be further reduced for fast extracted beam delivery of ~ 1 μs where the BIF-Monitor's exposure time ends before all neutrons have arrived. If the image intensifier is installed far from a beam dump or other neutron sources, for example in transport lines, the background is expected to be less pronounced.

REFERENCES

[1] see e.g. P. Spiller et al., these proceedings.

[2] see e.g. P. Forck et al., *Proc. DIPAC05*, p. 223, Lyon (2005) and references therein.

[3] P. Forck, A. Bank, *Proc. EPAC 02*, Paris, p. 1885 (2002) and A. Bank, P. Forck, *Proc. DIPAC 03*, Mainz, p. 137 (2003).

[4] R.H. Hughes et al., *Phys. Rev.* **123**, 2084 (1961), L.W. Dotchin et al., *J. Chem. Phys.* **59**, 3960 (1973).

[5] F. Becker, Diploma Thesis, Technical University Darmstadt (2006).

[6] C. Scheidenberger et al., *Nucl. Instrum. Meth.* **B 142**, 441 (1998).

[7] T. Kurosawa et al., *Phys. Rev.* **C 62**, 044615 (2000).

[8] H. Iwase et al., *JNST*, Vol. 39, No.11, 1142 (2002).