BEAM INDUCED FLUORESCENCE (BIF) MONITOR FOR TRANSVERSE PROFILE DETERMINATION OF 5 TO 750 MeV/u HEAVY ION BEAMs *

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Abstract

In the frame of the FAIR-project (Facility for Antiproton and Ion Research) at GSI, high intensity beams from protons to Uranium ions with energies ranging from 100 MeV/u to 30 GeV/u are foreseen [1]. Precise beam alignment in transport lines between the synchrotrons and in front of production targets is mandatory. Since the beam energy will be increased from todays 100 Joule to about 10^4 Joule per ion pulse, conventional intercepting beam diagnostics can not be used. For transverse profile determination a non-intercepting Beam Induced Fluorescence (BIF) monitor in residual nitrogen, using an image intensified CCD camera was investigated. The photon yield and background contribution were determined for different ion species, beam energies and N_2 pressures. The spectral response was mapped and associated with the N_2 transitions using narrowband interference filters. Profile distortions were quantified. Additionally, the appropriate layout for different diagnostic tasks is discussed.

THE BIF METHOD

As an alternative to the traditional SEM-Grids, the transverse beam profile in 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. When the beam collides with the residual gas molecules, some molecules are ionized remaining with a certain probability in an excited state. In a N_2 dominated residual gas composition, a strong fluorescence in the blue wavelength range 390 nm $< \lambda <$ 470 nm and a lifetime of about 60 ns is generated by a transition band to the

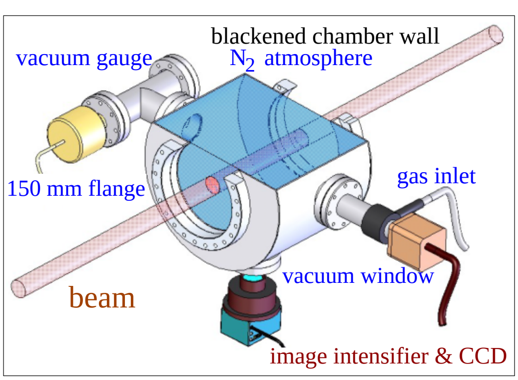

Figure 1: Scheme of a BIF-Monitor.

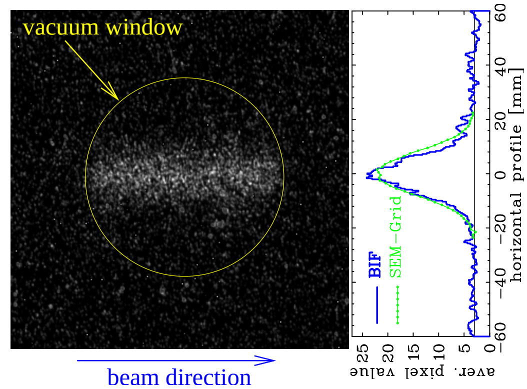

Figure 2: Image from a 1.5 μs long pulse of $2 \cdot 10^9$ Xe^{48+} at 200 MeV/u. The projected horizontal profile is compared to SEM-Grid data. The BIF data were recorded at $1 \cdot 10^{-3}$ mbar and averaged over 20 shots.

N_2^+ electronic ground state ($B^2\Sigma_u^+(v') \rightarrow X^2\Sigma_g^+(v'') + \gamma$, for vibrational levels v) [3]. 'Single-photon counting' was performed using 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 fire wire interface (Basler A311f). The device is mounted at a distance of 20 cm from the beam axis. A UV-transmitting quartz-lens with remote-controlled iris and focus and a focal length of 25 mm, leads to a resolution of 180 μm/pixel. In front of the lens a filter wheel equipped with 10 nm narrow band interference filters was installed in order to record spectral resolved beam profiles. The detailed description of the detection setup can be found in [4, 5].

During the last years the BIF method was applied successfully at the GSI heavy ion LINAC for various ion species and energies between 5 and 11.4 MeV/u [4]. In this paper its application for higher energies as extracted from the heavy ion synchrotron SIS18 is described. Beside the signal amplitude, the background contribution is of interest, due to the rising neutron production [6]. In order to cover the full range of aimed nitrogen pressures and beam energies, two different experimental areas were used. One is a LINAC-beamline for low energy (5 to 11.4 MeV/u) and low pressure investigation ($1 \cdot 10^{-6}$ to $1 \cdot 10^{-3}$ mbar). The other location is a high energy beam transport line (HEBT) behind SIS18. The BIF monitor was installed at a distance of 2.1 m from the beam dump and the corresponding part of the vacuum pipe was separated by 50 μm stainless steel vacuum windows to admit gas-pressures up to 1 mbar. This setup has been tested for Xe, Ta, U ions having energies be-

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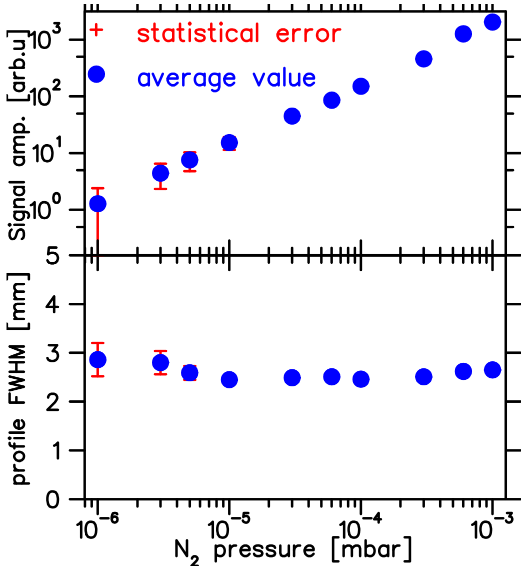

Figure 3: Total signal amplitude and measured profile width shown as a function of vacuum pressure, for a 5.5 ms long pulse of $4 \cdot 10^{10}$ Ni^{6+} at 4.54 MeV/u.

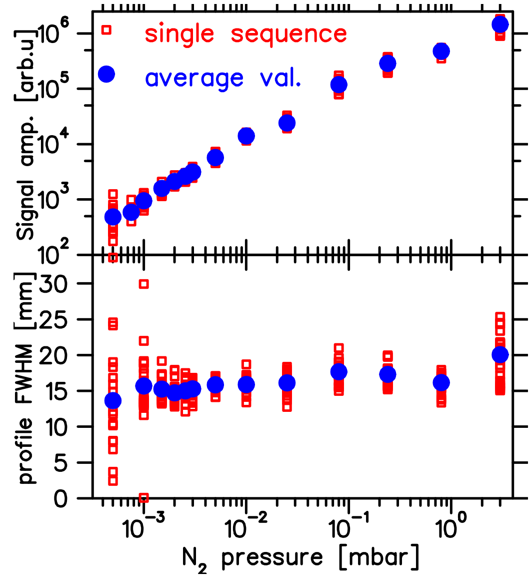

Figure 4: Total signal amplitude and measured profile width shown as a function of vacuum pressure, determined with the beam parameters of Figure 2.

tween 60 and 750 MeV/u in fast and slow extraction-mode. An example of a raw BIF image 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.

SIGNAL DEPENDENCE ON N_2 PRESSURE

The gas pressure acts as a free parameter to match the required photon statistics as the differential energy-loss, given by the Bethe-Bloch formula predicts a linear increase with the N_2 pressure. For a N_2 pressure rise over six orders of magnitude from 10^{-6} mbar to 1 mbar the experimental results confirm the prediction as the photon yield increases linearly, see Fig. 3 and Fig. 4, upper part. The second important result is that over this large pressure range the profile width remains constant within the error bars, see Fig. 3 and Fig. 4, lower part. This was not obvious due to the complex molecular physics involved in the excitation and fluorescence processes [3].

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 projected signal and the resulting amplitude is plotted in Fig. 5, top. Since the energy loss in matter is described by the Bethe-Bloch formula, parameters of the investigated ions were fitted to it, as shown in relative units in Fig. 5, top. The agreement with the measured signal amplitude is quite good, supporting the proportionality between energy loss and fluorescence yield.

The most critical issue for the BIF method is the background contribution. The background is uniformly distributed on the image and increases as a function of energy as summarized in Fig. 5, 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.

Therefore neutrons are the key background-source, which was confirmed by dose measurements and related neutron generation and distribution calculations, see [6, 7]. Since signal to background ratio decreases about two orders of magnitude for the investigated beam energies, Fig. 5, bottom, background reduction has to be achieved by short gating times and an effective neutron shielding. In order to gain space for shielding material surrounding the image intensifier without loosing solid angle, a fiber optics bundle will be used. These commercial systems consist of 1 million optical fibers arranged to perform a 1:1 imaging.

SPECTRAL INVESTIGATION

Nitrogen molecules are excited to vibrational levels corresponding to characteristic line spectra. At low pressures we expected the major contribution by directly excited N_2^+ with its strongest lines at 391.4, 427.8 and 470.9 nm. In this case possible profile distortions might occur due to the displacement of the N_2^+-ion during the decay time of 60 ns [3]. To investigate this excitation process in detail, we mapped beam profiles trough 10 nm narrow band interference filters with central wavelengths λ_0 at 390, 430 and 470 nm and compared their amplitude respectively transition strength and width σ, see Table 1 column 2 to 4. The spectral distribution agrees with former experiments [3]. Moreover the profile width σ remains constant within the

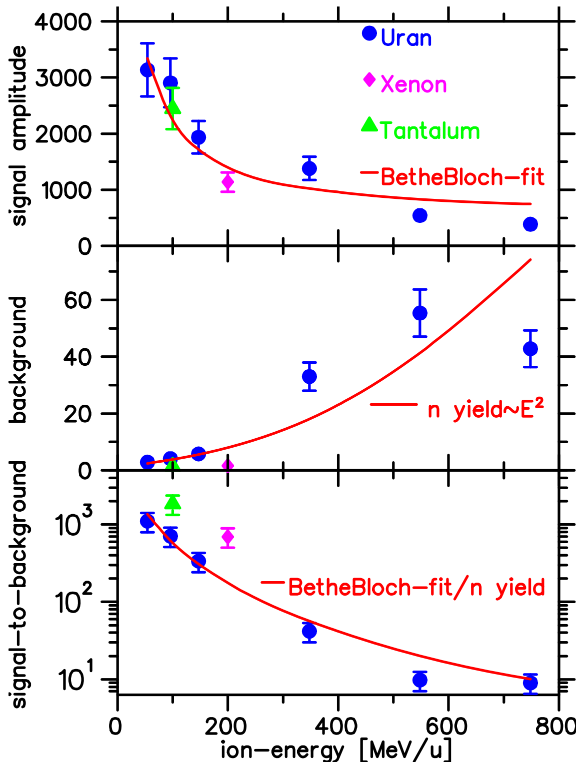

Figure 5: Total signal amplitude (top), background level (middle) and signal-to-background ratio (bottom) as a function of energy for the investigated ions. The amplitude for Xe and Ta were normalized by their charge and mass with respect to U. The background was normalized with respect to the mass only.

error bars for all pressures, beam energies and ion species. All measured beam profiles agree among each other and they are in accordance with standard SEM-grid profiles as exemplary shown in Figure 2.

For pressures $p > 1$ mbar, a 2-step excitation process becomes more important with an expected 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 to triplet-states leading to fluorescence-light in the near UV (337 nm $< \lambda <$ 358 nm). As the mean free path of electrons at 1 mbar is still about 1 mm, these electrons may travel a certain distance prior to the molecular excitation which leads to an additional profile distortion. We also recorded the strongest line of this 2-step process at $\lambda_0 =$ 337 nm and listed the results in Table 1, last column. As expected the profiles are significantly enlarged but as their contribution is below 1 %, it can be neglected for N_2 pressures below $1 \cdot 10^{-3}$ mbar. This again validates the results for the pressure variation, where the measured profile width does not change up to pressures of 1 mbar, see Fig. 3 and 4. To assure the reliability of measured beam profiles, spectral filters allow to select well known transitions, excluding unwanted 2-step processes. As for the FAIR-project [1] beam intensities will increase by a factor of 10^3 the required pressure bump will decrease by the same factor.

Table 1: Relative transition strength and corresponding profile width σ are given for different pressures and beam-parameter settings, $\delta\sigma \geq 0.5$ pixel.

λ_0 [nm]	390	430	470	337
trans.	N_2^+(0-0)	N_2^+(0-1)	N_2^+(0-2)	N_2 (0-0)
4.54 MeV/u Ni^{6+}, p =$1 \cdot 10^{-5}$mbar				
str. [%]	85±12	10±2	4.8±.7	0.1±.01
σ [mm]	1.02(9)	0.91(9)	1.16(9)	1.6(1)
4.54 MeV/u Ni^{6+}, p =$1 \cdot 10^{-3}$mbar				
str. [%]	87±13	12±2	1.3±.15	0.2±.02
σ [mm]	1.08(9)	0.99(9)	1.13(9)	1.99(9)
11.46 MeV/u Ni^{6+}, p =$1 \cdot 10^{-3}$mbar				
str. [%]	86±13	13±2	1.3±.2	0.2±.02
σ [mm]	1.96(9)	1.95(9)	2.13(9)	2.3(2)
200 MeV/u Au^{64+}, p =$5 \cdot 10^{-2}$mbar				
str. [%]	50±8	29±4.5	5±0,8	16±2.5

Even for high energy beam transfer conditions, according Fig. 2, N_2-pressures $\leq 1 \cdot 10^{-6}$ mbar will be sufficient and the N_2 (0-0) contribution can clearly be neglected.

CONCLUSION

The general functionality of BIF had been experimentally proven for the whole energy range from 5 to 750 MeV/u. Profile determination in single pass mode was performed for low energy LINAC conditions and HEBT conditions, even close to a beam dump. Careful investigation concerning signal strength, profile width, background distribution and the contribution of N_2 fluorescence levels have shown the BIF-monitors applicability for all available beam energies, ion species and required gas pressures. Future technical improvements will include chamber-geometry, lens-system, image intensifier, respectively the photo cathode. The major challenge will be the design and development of an effective neutron-shielding using a fiber optics bundle. Further investigation will concentrate on beam profile distortions due to the electrical field of high intensity ion beams. Also correction schemes based on precise modeling will be developed.

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