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INVESTIGATION OF ION TRAPPING AND BEAM-INDUCED FLUORESCENCE AT THE ELECTRON COOLER TEST-BENCH AT HIM*

T. Beiser†[1], K. Aulenbacher[1], J. Dietrich, Helmholtz-Institute Mainz, Germany
and GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[1]also at Johannes Gutenberg-University, Mainz, Germany

Abstract

Beam-current dependent and wavelength-resolved studies of the beam-induced fluorescence at the electron cooler test-bench recorded with a low-noise, cooled sCMOS-camera, will be presented. As a new feature, a high-voltage switch was utilized for beam interruptions, counteracting ion trapping.

BEAM-INDUCED FLUORESCENCE AT THE ELECTRON COOLER TEST BENCH AT HIM

The test bench uses an energy-recovery setup to produce an electron beam [1] with up to 1 A of 30 keV electrons for 3 kW of wall power (see Figure 1). Beam-induced fluorescence (BIF) was observed in the residual gas of the beam pipe at 3×10^{-10} mbar (see Figure 2). Most measurements were taken with 18 keV electrons and a current of 550 mA to limit the X-Ray exposure of the cooled, low-noise sCMOS camera. Images were acquired over 30 s, with a 400–550 nm bandpass filter to limit the black-body background generated by the thermionic cathode [2]. The resulting profiles were averaged over 500 pixel rows (see Figure 3).

The observed data showed an intensity increase of the BIF over time, plateauing after 3-5 minutes. This was noticeable even after normalizing for the change in pressure, a result of the collector heating induced by the dumped electrons. Taking this into account and measuring the BIF for a number of beam currents from 0 to 550 mA, a overproportional correlation of the integrated signal intensity with the beam current became evident (see Figure 4). This suggested the trapping of photon-emitting ions.

ION TRAPPING IN THE ELECTRON BEAM

Residual gas particles are ionized by the electron beam along its path. To explain the trapping mechanism, the DC electron beam of the test-bench can be approximated as a cylindrical homogeneous charge distribution. The grounded, small apertures of the anode and the deceleration optics along the beam path shape the beam potential and facilitate longitudinal trapping (see Figure 5), as long as the momentum transfer is small enough. A simple model was derived to explain the shape of the BIF. The measured BIF photons are most likely emitted by trapped ions that get excited by

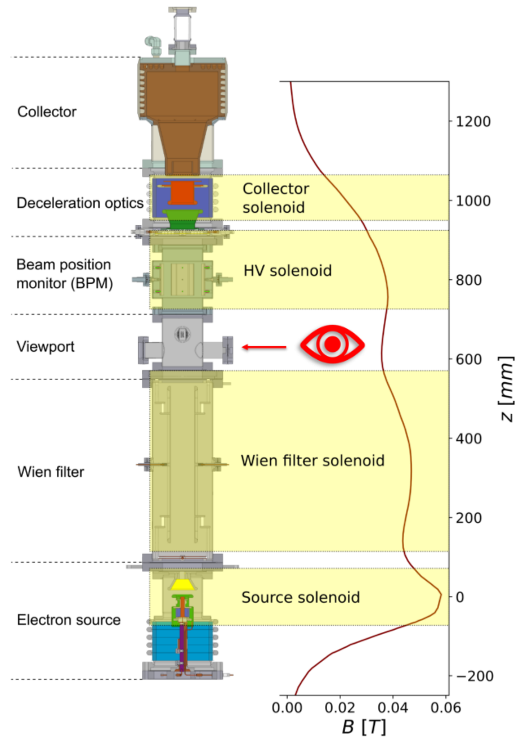

Figure 1: Schematic of the test bench with the simulated solenoid field-strength along the beam path.

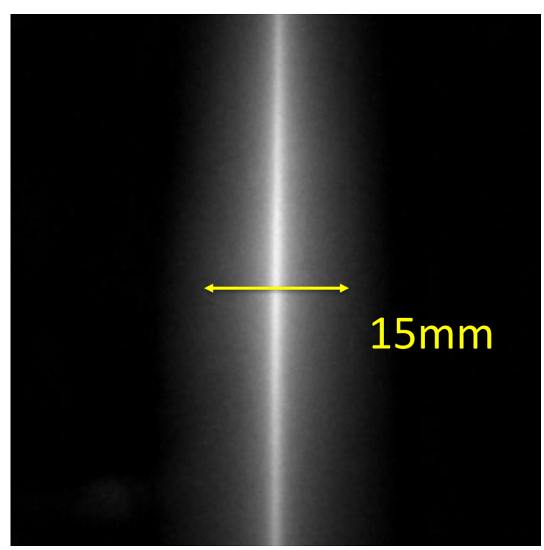

Figure 2: Image of BIF produced by a 30 keV, 1 A electron beam with indicated width.

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† thbeiser@uni-mainz.de

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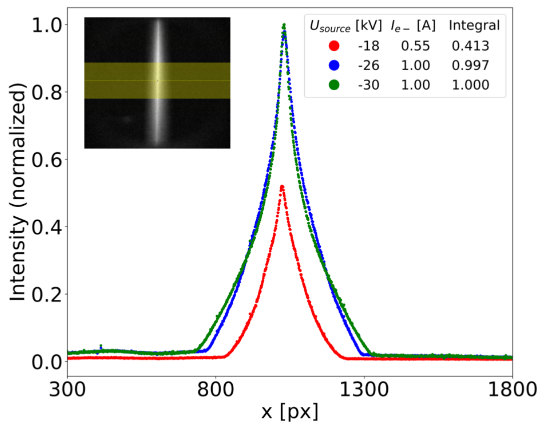

Figure 3: Averaged profiles of BIF for several parameters. (Averaged region indicated in yellow).

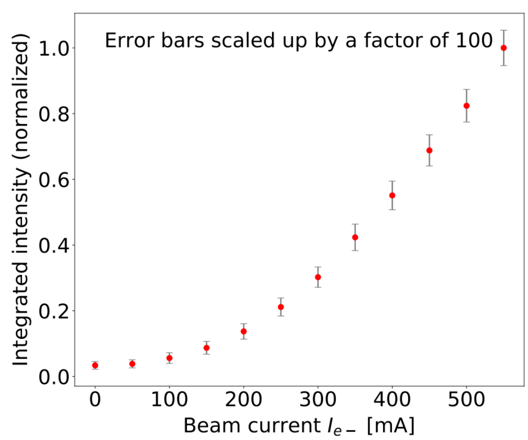

Figure 4: Integrated intensity of BIF profiles correlated with the electron beam current.

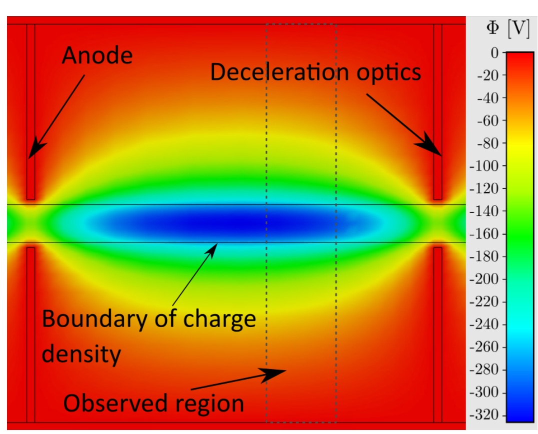

Figure 5: CST-simulated, simplified model of the test-bench and the potential of a homogeneous charge distribution (on the center plane).

the electron beam repeatedly. Particles do not interact with each other and do not change the electrostatic potential of the beam. Their motion is harmonic inside the potential, i.e. the oscillation period is independent from the starting position. The fact that all particles produced outside a given radius reach this radius at the same time may be taken into account by having a density distribution

$$\sigma(r) = e^{-r}/r. \tag{1}$$

This resembles a Laplace distribution. This model for the charge density of the ions diverges at r = 0, but this is also the point where the assumptions made about the ions break down.

Introduction of an amplitude parameter a, which is due to the fact that the observed signal is a projection of the ion distribution and a transition $r = \tilde{r} + \Delta r$ (with $\Delta r << r$) to avoid division by zero,

$$f_{fit} = \frac{a}{2\phi} \exp - \frac{|\tilde{r} + \Delta r + \ln(|\tilde{r} + \Delta r|) - \theta|}{\phi}, \tag{2}$$

with the location parameter θ and the scale parameter $\phi > 0$, can be fitted to the observed data (see Figure 6). Consequently, the position of the center of charge could be identified, and through the sharp transition of the signal into the background, the border of the electron beam was observed.

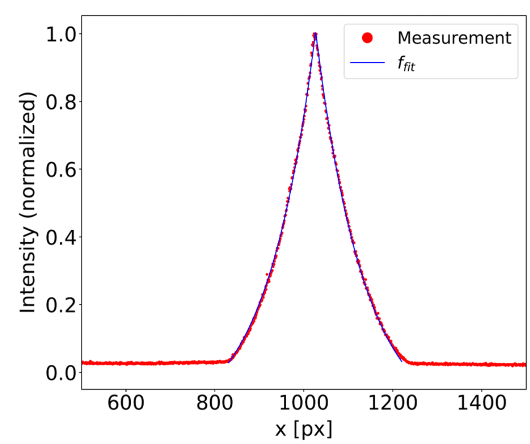

Figure 6: BIF profile of a 550 mA electron beam and the derived fit function.

ION CLEARING THROUGH BEAM INTERRUPTIONS

Following an experiment at the Recycler Electron Cooler at Fermilab a fast HV-switch was implemented at the Pierce electrode of the test-bench to interrupt the beam with 15 Hz [3]. Pulsing the electron beam in this way resulted in a decrease of BIF photons (see Figure 7). It takes about 4 ms to switch the electron beam off completely, because of the capacitive load of the Pierce electrode. The reduction in the number trapped ions was previously only indirectly observed via the cooling power of the beam (at Fermilab). Further measurements with different interruption frequencies were conducted to maximize the duty cycle of the electron beam while minimizing the number of trapped ions (see Figure 8).

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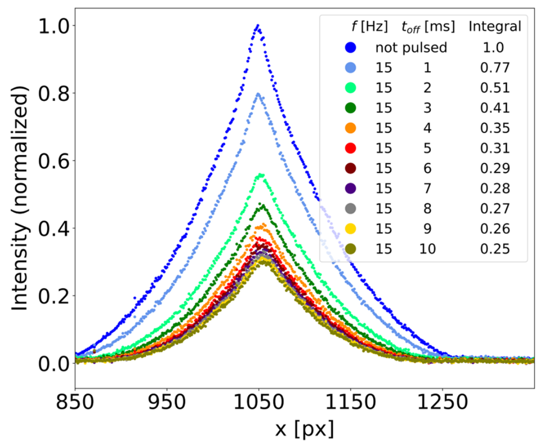

Figure 7: BIF profiles for a pulsed electron beam compared to a DC beam.

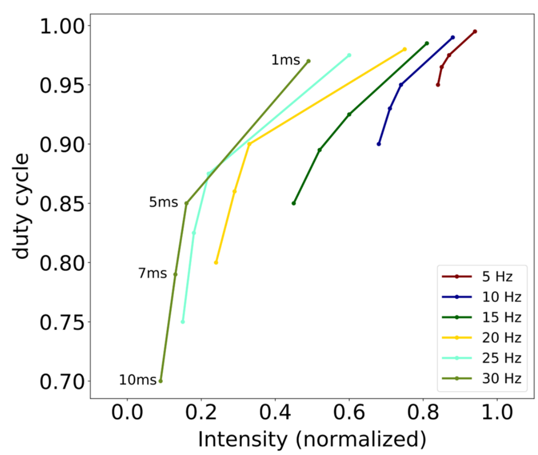

Figure 8: Duty cycle for several pulsing frequencies and switch-off durations.

SPECTRALLY-RESOLVED BIF

The test-bench has similarities to an EBIT (Electron Beam Ion Trap). In such devices a background of Barium is often detected during optical measurements, caused by the widely used Barium dispenser cathodes [4]. A comparable Ba dispenser cathode is installed at the test-bench. The H_2 spectral lines, expected in a baked out ultra-high vacuum vessel like the test-bench, are not present. Considering the partial pressure of Barium that develops in the beam region due to evaporation according to the manufacturer ($p_{Ba} = 1.37 \times 10^{-10}$ mbar), which is higher than typical for H_2 in such a vacuum vessel ($p_{H_2} = 5.64 \times 10^{-11}$ mbar) and the corresponding electron-impact ionization cross-section of Barium that is about 5 times higher than the one of H_2 ($\sigma(H_2) = 0.02\,\mathring{A}^2$) at the given energy, the data could potentially be explained by different charge states of Barium. The charge density of the electron beam is relatively low compared to an EBIT, so it is not certain if they are present (see Figure 9).

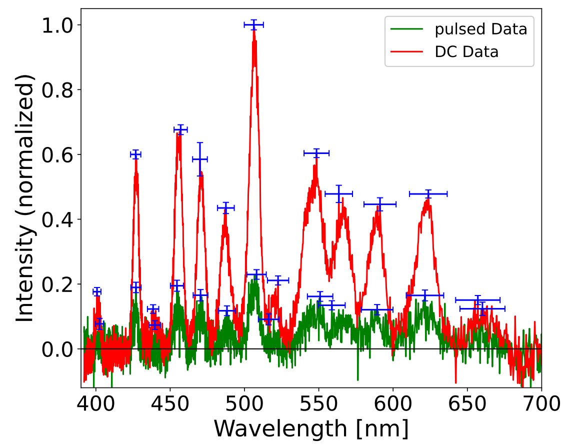

Figure 9: Spectrally-resolved measurements comparing DC and pulsed beams (at 15 Hz, integrated over a 550 mA electron beam switched on for 10 h each).

CONCLUSION

We observed beam-induced fluorescence (BIF) emitted by continuously excited ions, which were created and trapped by the electron beam itself. These photons allowed us to locate the center and the borders of the electron beam. Ion clearing through beam interruptions was directly measured with the BIF. The obtained BIF spectrum suggested that the Barium evaporating from the dispenser cathode installed at the test-bench might be a source of particles ionized by the electron beam.

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