COMMISSIONING OF THE DETECTION SYSTEM FOR A SUPERSONIC GAS-JETS BASED TRANSVERSE BEAM PROFILE MONITOR*

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Abstract

We present the commissioning results of the Micro-Channel-Plate (MCP) based, ion extraction and detection system currently in use for an experimental test stand aimed at demonstrating the operation of a least-interceptive transverse beam profile monitor based on a planar supersonic gas jet. This monitoring design features least-interceptive operation under excellent vacuum conditions and provides fast acquisition of a bi-dimensional transverse profile. It bears application for ultra-low energy particle beams at future storage rings, but also for e.g. linacs at high currents and light source injectors. For instance, the Ultra-low energy Storage Ring (USR), part of the Facility for Antiproton and Ion Research (FAIR) in Germany will store antiprotons at energies of 20-300 keV. In this contribution, we report numerical simulations and experimental results obtained by calibration of the detection system with a low energy electron beam to demonstrate a 1 mm imaging resolution only limited by recoiling ion drift.

INTRODUCTION

Low-energy physics and storage rings are recently attracting growing interest in the scientific community, as characteristics of quantum systems are most conveniently studied at low projectiles energies in the keV range [1].

Development of low-energy storage rings causes widespread beam diagnostic technologies to become obsolete. In particular preservation of the beam lifetime causes perturbing profile monitoring, such as interceptive foils, to be ruled out [2]. Furthermore, existing non-perturbing techniques such as residual gas monitors can take up to about 100 ms to make meaningful measurements, due to the low residual gas pressure, at the expected operating pressure of around 10^{-11} mbar [3].

A possible solution around these limitations is a neutral supersonic gas jet target, shaped into a thin curtain, and bi-dimensional imaging of the gas ions created by impact with the projectiles. Keeping the curtain at a 45^{o} angle from the impinging direction of the projectiles, and extracting the ions perpendicularly to the jet-projectile beam interaction plane on a position sensitive detector, an image of the projectile beam transverse section is formed on the detector, much like a mirror reflection [3].

We note that usually the positive ions are detected in such monitors, as well as in the residual gas monitors, which operate on a similar detection system, rather than the electrons, as the far larger velocity of the latter would require the use of a magnetic field

This monitor becomes hence the monitor of choice for multi-pass, low-energy, ultra-high vacuum storage rings such as the Ultra-Low Energy Storage Ring (USR), to be installed at the Facility for Low energy Antiproton and Ion Research (FLAIR), within the FAIR facility planned at GSI in Darmstadt, Germany [1].

The experimental setup for such monitor is also fully suited for applicability as a residual gas monitor, due to the equivalence of the detection systems of the two monitoring solution, which extend also to the large area of several centimeters interested by the extraction field and therefore imaged on the MCP detector. Furthermore, operation of the supersonic jet setup as a residual gas monitor also provides access to essential information on the resolution and reliability of the detection system. This is important for commissioning purposes before the supersonic jet can be operated.

An test stand for the demonstration of the supersonic jet profile monitoring system has been designed and commissioned, and is now operational at the Cockcroft Institute, UK. It has been fitted with an additional imaging phosphor screen and a precision leak valve for thorough characterization of the detection system in the residual gas operation mode.

APPARATUS DESCRIPTION AND SIMULATION

A full set of simulations for detailed characterisation of the extraction system has been carried out with the electrostatic and particle tracking simulation package of OPERA 13.0. The simulations focused on assessing detection resolution and field homogeneity, which reflects on the homogeneity of sensitivity in the measurements.

The extraction system included in our apparatus is shown in Fig.1. It is composed of 8 extraction electrodes with 14 mm spacing, a repeller plate 72 mm below the last electrode, and 2 final acceleration grids which allow choosing the energy at which the collected ions impinge on the MCP, for optimum and controlled amplification. The precision machined ceramic spacers allow positioning of the electrodes to within 200 μm of the nominal position. They are screened with stainless steel shields (shown in blue in Fig.1) to avoid charge collection on the ceramic which would result in a field, and hence image distortion.

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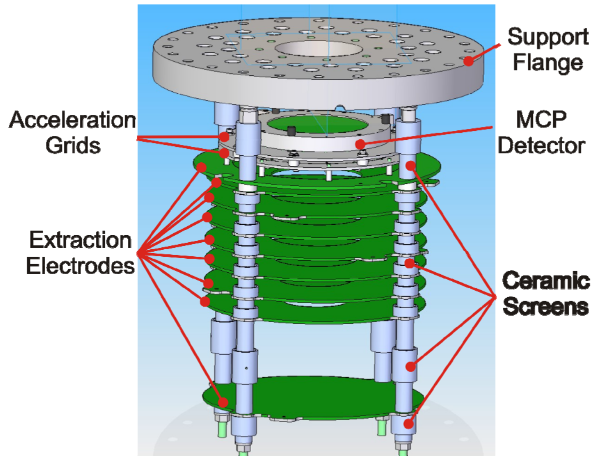

Figure 1: CAD of the extraction system included in the supersonic gas jet based beam profile monitor.

The distortion effects in the field due to the large spacing between the repeller plate and the last electrode are compensated by choosing large outer diameters and small inner bore diameters for the electrodes: simulations show that the homogeneity of the field, defined as the percentage deviation from the design field, amounts to less than 3% in the detector observation region of 70 mm diameter around the system axis.

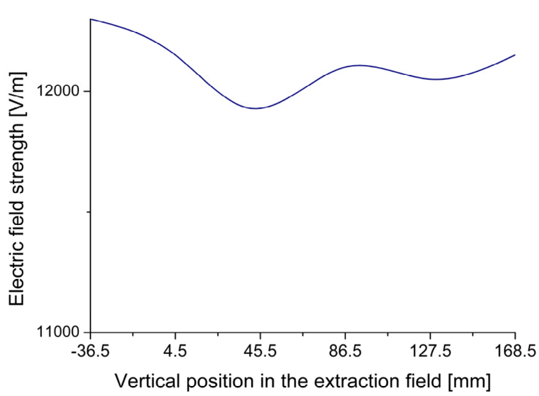

Figure 2: Vertical component of the extraction field: deviations from the design value amount to < 3%.

This inhomogeneity affects the time of flight of the collected ion from its point of creation to collection at the detector. In turn, any delay on the time of flight results in a larger transversal drift under the effect of the initial velocity of the ionized atom due to projectile impact recoil. However, transverse drift is inversely proportional to the square root of the electric field, and the contribution to it from the 3% variation of the field turns therefore into a <1.5% variation in time of flight. Therefore, transverse drift would also be affected at < 1.5% level, depending on the position the atom is created in; such figure is negligible with respect to the influence of the variability of initial momentum coming from thermal energy and projectile impact momentum transfer.

The limits on the resolution of the monitor come thus from the drift due to initial transverse momentum. The initial transverse momentum distribution is affected by two contributions: the thermal velocity and the momentum transfer due to the impacting, ionizing projectile. The initial transverse momentum will be therefore described by the convolution of the thermal Maxwell velocity distribution with the impact ionization momentum transfer distribution. High precision experiments show that momentum transfer due to impact ionization is always in the order of a few a.u. [4], and turns out to amount for low energy electron projectiles such as the ones used in our experiments, at 4.5keV, to about ½ the value of the average thermal momentum at room temperature.

When the monitor is used in the supersonic gas-jet operation mode, the thermal drift is greatly reduced, as the internal temperature of the jet is smaller than a few K [4]: in such conditions, the impact momentum transfer becomes dominant. However, the forward velocity of the molecules in the jet introduces a forward bias in the drift. A particle tracking simulation for this case as it applies to the extraction system described earlier in this section is shown in Fig.3. The simulation assumes a 12kV/m extraction field, a 4.5keV electron beam and a cold (1 K) argon gas jet travelling at 1000m/s.

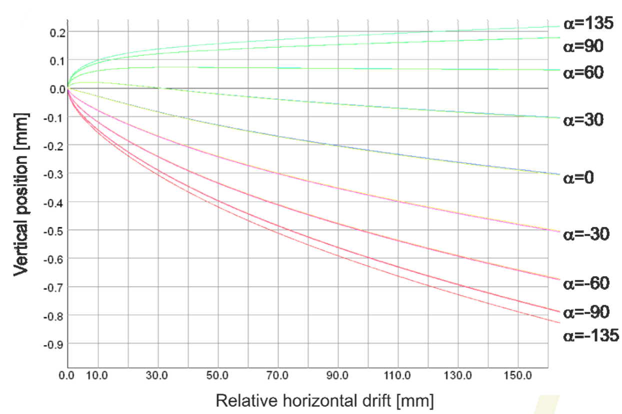

Figure 3: OPERA particle tracking simulations. The different tracks correspond to the trajectories of ions with different initial momentum direction, as described by the angle α formed with the horizontal. α = ±135° corresponds to the outermost tracks (maximum ballistic range from trivial kinematic considerations), hence their distance at the detector level (z = 150) expresses the resolution of the monitor: about 1 mm.

It can be seen that the spread to be expected at the detector (longitudinal coordinate z = 150mm in Fig.3) from such configuration is about 1mm, improvable by increasing the extraction field value. The maximum value for the extraction field is limited by the beam dynamics requirements for the accelerator section in which the monitor needs to be installed, and always needs to be corrected for by installing an opposite correction field.

When considering operation as residual gas monitor, the spread resulting from the convolution of thermal drift and impact momentum transfer can be effectively approximated with a Gaussian distribution. Assuming the impinging beam is Gaussian distributed, the transverse width of the observed beam σ_{obs} as read on the CCD camera, measured in pixels, can be expressed in terms of its true width σ_{beam} in mm, the transverse spread due to ion drift σ_{drift} in mm and the conversion ratio $R_{pix/mm}$ describing how many pixels correspond to one mm, as summarized in eqn. 1:

$$\sigma_{obs\ [pix]} = \sqrt{\sigma^2_{beam\ [mm]} + \sigma^2_{drift\ [mm]}} \cdot R_{pix/mm} \tag{1}$$

Rearranging yields the following relation:

$$\sigma^2_{obs\ [pix]} = \sigma^2_{beam\ [mm]} \cdot R^2_{pix/mm} + \sigma^2_{drift\ [mm]} \cdot R^2_{pix/mm} \tag{2}$$

Therefore, if σ_{obs}^2 is plotted against σ_{beam}^2, the points should lie on a straight line from whose gradient and intercept $R_{pix/mm}$ and σ_{drift} can be evaluated.

EXPERIMENTAL TESTS

In order to experimentally benchmark the OPERA simulations and calibrate the monitor, the setup was used in the residual gas operation mode. Therefore, the chamber was flooded with pure N_2 through a precision leak valve suitable to reliably control the pressure in the vacuum chamber and adjust it to a high enough level that the electron beam can be imaged by interaction with the residual gas. The image from the detector is captured by a CCD camera and the image post-processed to yield σ_{obs}. The apparatus is furthermore equipped with an additional phosphor screen which is directly hit by the electron beam and is used to directly measure σ_{beam}.

For the measurement σ_{beam} can be scanned across the range 2.5 to 13.5 mm by adjusting the focus settings of the electron gun: the focal length of the electron gun is chosen so that the variation in beam width within the observation area and up until the direct hit phosphor screen stays constant to below measurement resolution.

Fig.4 shows a set of measurements taken with a 9kV/m extraction field at a $3\cdot10^{-6}$ mbar base pressure. The error bars are comparable with the dimension of the points in the plot, and resulted mainly from the uncertainty in the measurement of the true beam size on the direct hit phosphor screen (horizontal bars) and from the background noise of the MCP detector (vertical bars). The very good fit to a straight line (Pearson value > 0.99) of the data point confirms the applicability of eqn. 2 to describe the ion drift phenomenon. Moreover, the gradient and intercept from Fig. 4 translate in a value of $R_{pix/mm} = 5.3$ and $\sigma_{drift} = 1.43$ mm, thus compatible with an imaging resolution < 200 µm and a measurement resolution as limited by ion drift of <1mm at the design field of 12kV/m with a cold target.

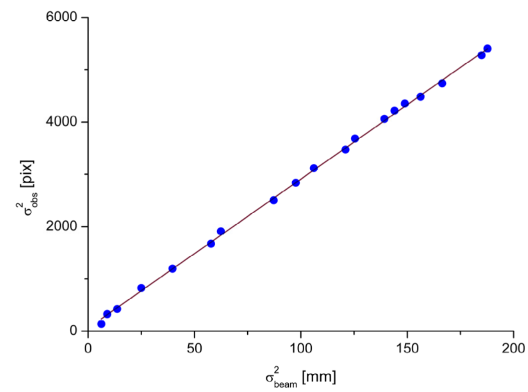

Figure 4: Experimental determination of the beam width squared as observed by the detector against the beam width directly measured on the phosphor screen.

CONCLUSIONS AND OUTLOOK

In this contribution we have reported on the commissioning status of a supersonic gas jet based transverse beam profile monitor.

A numerical analysis of the detection system carried out with the OPERA code has been shown to predict a limitation in space resolution due to ion drift of about 1mm. Simulations also show the homogeneity of the extraction field to be good enough to have a negligible impact on the spatial resolution. Experimental tests carried out to calibrate the detection system by means of direct particle beam width observation confirm the predictions made by numerical OPERA simulations.

Experiments to fully characterize the monitor, making use of the detection system detailed in this contribution are currently being carried out at the Cockcroft Institute, UK.

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