Development of Residual Gas Profile Monitors

at GSI

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Abstract. Beam profile measurements at modern ion synchrotrons and storage rings require high timing performances on a turn-by-turn basis. High spatial resolutions are essential for cold beams and beamwidth measurements. The currently used RGM supported very interesting measurements and applications. Due to the readout technology the spatial and time resolution is limited. To meet the expanded demands a more comprehensive device is under development. It will be an all-purpose residual gas monitor to cover the wide range of beam currents and transversal particle distributions. Due to the fast profile detection it will operate on primary electrons after residual gas ionization. A magnetic field of 100mT binds them to the ionization point inside 0.1mm orbits. The high resolution mode will be read out by a digital CCD camera with an upstream MCP-phosphor screen assembly. It is planned to read out the fast turn-by-turn mode by an array of 100 photodiodes with a resolution of 1mm. Every photodiode is equipped with an amplifier-digitizer device providing a frame rate of ~ 10MSamples/s.

1. INTRODUCTION

Residual Gas Monitors (RGM) provide a non destructive beam profile measurement of an circulating ion beam. Applications are the detection of transverse beam profiles in dependence of injection matching [1], hollow beam prevention, coupling resonances, beam cooling effects, etc. These different applications call for a detector that is capable to provide a spatial resolution down to 0.1mm for cooling and hollow beams and a frame rate up to 10MSamples/s to determine an optimal matching condition at injection. To span the variety of applications we are developing an RGM that provides two different modes of operation realized in one device. A high resolution readout via digital CCD camera and a high speed readout by photodiodes is in preparation.

The beam interacts with the residual gas within the beam line and produces residual gas ions and electrons (Fig. 1a). An electrostatic field E1 accelerates the ionization products (ions or electrons) towards a Micro Channel Plate (MCP). When the particles reach the MCP surface secondary electrons are produced and are accelerated into the channels by E2. Inside the channels they are multiplied by a factor of about $10^6$ (Chevron configuration). A wire array behind the MCP collects the secondary electrons and is connected to an adequate electronic device (current to voltage converter and adc). Placing a phosphor screen behind the MCP is another readout method (Fig. 1b). The secondary electrons hit the phosphor which is mounted...
downstream of the MCP. At the impact points lightspots are produced. These spots can be observed by a CCD camera, photo-diodes or other light detectors. For precise beam observations during acceleration or cooling, a high spatial resolution down to 0.1mm is needed. The exposure time of one beam profile will cover the 0.1-10ms range. In this case the beams image on the phosphor screen is observed with a digital CCD camera providing the required frame rate up to 100fps (frames per second). To realize the fast readout (one profile per synchrotron revolution) an array of photodiodes with a spatial resolution of 1mm and a repetition rate of about 100ns (10MSamples/s) is foreseen. The fast readout mode necessitates the detection of electrons. To bind the residual gas electrons to the ionization point a magnetic field of about 100mT is needed. By the way the magnetic field works against the space charge effect of cold or high intensity beams.

The currently used RGM revealed its usefulness in ion beam monitoring and enabled specific measurements, chapter 2. The low spatial and time resolution calls for a more comprehensive device, described in chapter 3.

2. CURRENTLY USED RGM

The currently used RGM in the heavy ion synchrotron at GSI enables important measurements concerning electron cooling, injection mismatches resulting in hollow beams, acceleration and extraction of the beam. Pictures of the RGM are shown in Figure 2a–2c. The duration of one measurement (one beam profile) can be switched between 0.5 and 5ms. Every 10ms a new measurement starts. The detector operates on residual gas ions which are accelerated by an electrostatic field of about 300 to 450V/cm. The amplification is done by two MCPs in Chevron configuration (Fig. 2c).
The dimensions of the MCPs are 100mm x 30mm and the active area is 100mm x 26mm. They are fixed in two sockets of glass ceramics and are fitted with two flat metal springs which are gold coated. An array of 64 wires with diameters of 1.5mm and distances of 0.6mm to each other is placed behind the MCPs. This wire array configuration determines the spatial resolution of 2.1mm.

The black plates in fig. 2a are made of glass and are covered with Germanium on the inner surfaces. A voltage of 4.5kV to 7kV is applied to the top sheet while the lower sheet respective the MCP surface are on ground potential. Difficulties with current break throughs via the Germanium surfaces forced us to develop a new electric field box. Figure 3a–3c show the results of two different electrostatic field simulations and the final mechanical design.

Figure 2: a) Picture of the currently used RGM in the heavy ion synchrotron at GSI, mounted on a flange of 300 mm diameter b) extraction area of ionization products, MCP holder and wire array c) MCP module in Chevron configuration, MCP size 100mm x 30mm, active area 100mm x 26mm, flat springs covered gold, sockets of glass ceramics.

Figure 3: Electrostatic field box with field forming high voltage blades. Picture a and b show the results of simulations with and without field forming blades for the electrostatic potential. Picture c shows the final mechanical design.

Straight electrostatic field lines between the top and bottom are important for obtaining an undistorted image of the beam. The main improvement of the new E-field box are the 4 blades at the entrance and exit of the beam path (Fig. 3b and 3c). The equipotential lines in Figure 3a are more curved in comparison with Figure 3b. The blades are on a higher (±4kV) respectively lower potential than the corresponding sheets (±3.5 kV). The limiting factor of the length of an E-field box is usually the
diameter of the flange. The blades improve the field quality significantly whereby the length of the E-field box is constant.
To test the MCPs, a deuterium lamp (115 ~ 400 nm spectral distribution) is placed above the E-field box outside the vacuum chamber. It shines through a glass flange and the E-field box onto the MCPs. Thus the bottom of the box is made of a metallic grid.

Figure 4 shows the measured signals of a synchrotron cycle with 3 injections while cooling at injection energy of 11.4 MeV/u. Every 500 ms an injection started. Finally, $6 \times 10^7$ ions of $\text{Xe}^{47+}$ circulated in the synchrotron and were accelerated to 600 MeV/u within 0.5 s. Every profile was measured in intervals of 10 ms with an integration time of 0.5 ms/profile. Plotting profiles on top of each other makes it easy to visualize the changes of the profiles' shape during the cycle (Fig. 4a and 4d). The color alteration of the plotted profiles starts blue and turns red later in the cycle. Red profiles are not seen due to the decay of the signal at extraction. The beam latitudes of the whole cycle were plotted with 10 ms time resolution (Fig. 4b and 4e). The profiles' shape gets narrower and the profiles' height increases during electron cooling. The beamwidth was measured at FWHM. Due to the overlaying of the first cold beam (large narrow profile) and the new not cooled beam (flat and wide profile) the beamwidth evaluated after each following injection is smaller than after the injections before. In Figures 4c and 4f the calculated integration (along abscissa in a, d) of the beam profiles is shown.
Figure 5 shows measurements based on a misadjustment of a steerer magnet in the transfer line between UNILAC and synchrotron. A hollow beam is seen in Figure 5a. After correction of the magnet settings profiles 5b and 5c were recorded. Due to the high data quality of the 3 measurements the corrections were completed within a few cycles.

![Figure 5: Measurement of a hollow beam in vertical direction. a shows the results of a misadjustment of a steerer magnet in the transfer line between UNILAC and synchrotron. b and c show the signal after correcting the magnets settings.](image)

Figure 6 shows an interesting measurement. The shapes of the horizontal and vertical profiles were exchanged between two measurements (10ms). The basic effect could be a coupling tune resonance between horizontal and vertical phase space. The low time resolution of the detector inhibited further studies.

![Figure 6: Pictures a and b show the horizontal beam profiles, c and d the vertical, between profiles 64 and 65 the profiles shape was exchanged while the position of the beam did not change.](image)

The fast non-destructive measurement proves the big capacity of residual gas monitors for the operation and fast and exact adjustment of accelerators.

3. NEW RESIDUAL GAS MONITOR

The currently used RGM showed the possible fields of applications and operations and produced interests of more detailed beam detection that it cannot fulfill. To achieve high spatial and time resolutions a new detector will be designed for determination of beam profiles during injection, cooling, acceleration and extraction. Furthermore the
device has to provide the features and properties needed for ambitious accelerator experiments like measurements of injection mismatches [1], detailed observation of coupling resonances and coherent betatron oscillations [2] on a turn-by-turn basis. High resolutions in time (100ns/measurement) and space (0.1mm) are the basic parameters of this development. The space resolution is limited by the MCP (chevron configuration). To conserve the space resolution of the MCP a phosphor screen and readout by a digital CCD camera are the most reasonable solution. The optical readout condition (phosphor screen) leads to an array of photodiodes for the high speed mode. Every photodiode is equipped with an amplifier-digitizer channel. A spatial resolution of 1mm in the fast mode is sufficient. Furthermore the fast mode requires electron detection and a fast phosphor screen. The fast phosphor screens e.g. P47 are near the ultraviolet range (400nm) and provide decay times of 60 ns.

During ionization the electrons are pushed out of the ionization point by the atomic scattering kinematics. To keep the electrons perpendicular to the ionization point a magnetic field is applied parallel to the external electric field. The strength of the magnetic field should be of about 0.1T and the electric field of about 0.5kV/cm. Within 4-7ns the primary electrons are guided inside a cyclotron diameter of 0.1mm towards the MCP as calculated for Fig. 7. The parameters are typical for a high current operation of the SIS synchrotron at GSI. The field uniformity from the ionization point to the MCP surface has to be in the range of 95%. In general the cyclotron radius is given by the initial electron velocity after ionization [2]. Due to the circulating electrons around the magnetic field lines the MCPs amplification factor decreases. Applying a higher voltage to the MCPs compensates this effect. The magnetic field can be provided by a rod type permanent magnet [3] or by a window frame magnet. Concerning the overall length and fringe field effects rod type permanent magnets seems to be the best solution. Permanent magnets are failsafe concerning the higher voltage at the MCPs. Windowframe electro magnets are another possibility however they require special precautions due to voltage breakdowns concerning the MCPs. The advantage is the possibility to switch them off.

**Figure 7:** Trajectories of ionized particles with and without a magnetic field. U$_{73}^+$ with $10^9$ ions at a bunch length of 10 m.
While the electrons are travelling towards the MCP the residual gas ions move to the opposite potential and produce secondary electrons when they hit the environmental parts. Secondary electron suppression is essential to avoid signal corruption.

The two different readouts (CCD and photodiode) get their signals from the same phosphor screen. One possible solution is the use of a mirror (Fig. 1b), which reflects the light from the phosphor either to the CCD or to the photodiodes.

The readout electronic of the photodiodes require a data acquisition system with 10MHz bandwidth and optimal noise and dynamic range [4]. It is separated into 4 stages. A conventional transimpedance amplifier in the first stage to amplify the signal immediately behind the photodiode. The next stage is a variable gain amplifier that provides the connection between the first stage and the adc and adjusts the obtained signal to the adc range. The third stage is a 14bit, 40MSamples/s adc. A DSP with a native interface to the adc and a built-in SDRAM controls the digital electronic and provides the connection to the PC. The DSPs 16bit, 32MB SDRAM, the 66MHz access frequency and the DMA (direct memory access) offers the possiblity to record long time sequences.

The E-field box is placed inside the vacuum while the magnetic device due to vacuum bakeout resides outside. The MCP-phoshor-assembly, the glass flange, the mirror and eventually the feed throughs are placed between the electric field box and the magnet device. This enlarges the gap between the magnet poles. Everything inside the gap has to be designed as small as possible. The whole detector consists of 4 magnets. A horizontal and vertical and two compensation magnets. To cover a wide range of applications and locations it will be possible to detect either electrons or ions. In case of ion detection the large magnet devices can be removed and the E-field boxes are placed nearer to each other in beam direction. This allows the use of the detector in environments of less space and make the detector all-purpose.

4. CONCLUSION

Important measurements have been performed with the existing residual gas monitor. Due to the chosen anode technology it's spatial and time resolution is limited. The new detector will be a very flexible and modular detection system, which covers a wide range of applications. We will integrate two modes of operation: a high spatial resolution mode by a digital CCD camera and a fast turn-by-turn mode read out by a photodiode array. The detector will operate on electrons supported by a magnetic field parallel to the electrostatic extraction field. The electrons are multiplied by two MCPs and the readout is done via a phosphor screen. To enlarge the number of applications it will be possible to detect residual gas ions too. The combination of a high spatial resolution and a fast readout makes the RGM to be a multi-purpose installation, which is capable delivering the very valuable information about transverse ion beam distributions.
REFERENCES

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