Abstract

The beam currents of the high energy heavy ion beam, extracted from the SIS at the GSI, Darmstadt, are routinely determined with three types of detectors: Scintillation counters in the range up to \(10^6\) pps, ionization chambers (between \(10^3\) and \(10^6\) pps) and secondary electron monitors (between \(10^3\) and \(10^{11}\) pps). The performance of these devices, and in particular the high intensity limits of the ionization chamber are discussed. As an application, the time structure of the slowly extracted spill is measured with the scintillators, which give a non-integrating, dead time free analyzing system in the frequency domain.

1 PARTICLE CURRENTS OF SLOWLY EXTRACTED IONS

The GSI heavy ion facility can deliver the whole spectrum of heavy ions in a wide energy range. Using the heavy ion synchrotron SIS, ions from p to U can be accelerated to energies from 50 MeV/u to 2 GeV/u. The number of stored particles in the SIS ranges between \(10^4\) for rare isotopes and a few times \(10^{11}\) for e.g. Ne. Most of the experiments use the slow extraction mode with a spill length between 0.5 s and 10 s. This is equivalent to about \(10^4\) pps (particles per second) and \(10^{11}\) pps, or, expressed in electrical current between 0.1 pA and 100 nA. These low, quasi dc currents cannot be measured with standard current transformers. Instead, other techniques are used: Low numbers of extracted ions are counted directly with plastic scintillators. For an intermediate range of particles gas filled ionization chambers (IC) are used. Since several decades this device is used for proton and heavy ion beams e.g. at CERN[1], LBL[2] and KEK [3]. As shown below, there is a drop of the efficiency (here called saturation) for particle rates higher than about \(10^4\) pps for heavy ions (depending on the ion species). To cover also the higher intensity range, secondary electron monitors (SEM) are used. Again, these devices are used since a long time e.g. at CERN[4]. Their current output is about three orders of magnitude lower compared to the ionization chamber and also their absolute precision is about a factor of 2 lower than for the IC.

2 DETECTOR HARDWARE

We developed a compact array of these three detector types, mounted on a pneumatically driven feedthrough on one Ø200 mm flange, see Fig. 1. The SEM is installed on the vacuum side, while the gas filled IC and the scintillators are accessible from outside. To prevent the scintillator from radiation damage, it can be moved separately with respect to the IC. These arrays are now installed at 12 different locations i.e. at critical points inside the high energy beam lines and close to the targets and are used routinely by the operators.

The plastic scintillating material is the well known NE102A (now BC400) with the size \(70 \times 70\) mm\(^2\) and a thickness of 1 mm. With standard electronic an average count rate of \(10^6\) pps can be achieved. But due to the spill structure (see section 4) the momentary count rate (within \(100\) μs) can easily exceed \(10^7\) pps.

The ionization chamber is constructed with the electric field parallel to the beam particle velocity and is mounted inside a cylindrical tube (together with the scintillator). It is separated from the vacuum by a 100 μm stainless steel window. The electrodes of the chamber are made by 1.5 μm Mylar and are coated with 100 μg/cm\(^2\) silver; the thin foil is used to prevent for the emission of secondary electrons from the surface. The electrodes are separated by 5 mm and an electric field between 1kV/cm and 4 kV/cm is applied. The size is \(64 \times 64\) mm\(^2\) and a mixture of 80% Ar and 20% CO\(_2\) is used as the counting gas. More details can
be found in [6, 7]. The current from the IC is measured by a current-to-frequency converter, which has a range from 1 pA to 10 µA [8]. The converter is installed close to the device. Using the well determined W-value (average energy for creating an ion-electron pair) for Ar and CO₂ and an analytical calculation of the energy loss [9], the amount of extracted particles can be determined. The IC is calibrated versus the scintillation counter, and from a series of measurements we can state an absolute precision compared with the calculation to be 10 % [7]. The relative uncertainty (i.e. comparing ICs installed at different locations in the beam line with the same ion beam) is below 3 %.

The SEM is mounted on the same tube as the IC, but inside the vacuum. It consists of 3 slightly curved 100 µm Al plates to increase their mechanical strength and to prevent microphonic pickup. The size of the electrodes is 80 × 80 mm² and 100 V is applied. While Al is easy to handle from the mechanical point of view, it has the disadvantage to be sensitive to radiation damage, due to surface modifications [10]. But because we do not use it as a permanent installation inside the beam, no substantial decrease of the secondary emission coefficient has been measured yet. As a fitted value from a large amount of calibration measurements we determined a yield of Y = (27.5 ± 0.5) e⁻⁻/cm²/(MeV/mg/cm²) [7]; this is the fraction of emitted secondary electrons per unit of the specific energy loss. Within our uncertainty, Y does not depend on the ion’s nuclear charge. The current output is about three orders of magnitude lower as compared to the IC and it is measured with the same type of electronics. The absolute accuracy of 20 % is lower as compared to the IC, and the relative accuracy is about 5 %. The SEM can be used for the highest possible ions currents delivered by the SIS, no saturation has been detected so far.

3 THE IC HIGH INTENSITY LIMIT

The IC is a very useful and reliable device and is used routinely for the slowly extracted ion beam. As an example for limitations for higher intensity we like to report on a measurement with Ne⁰⁺ of 300 MeV/u, see Fig. 2. The main result is the drop in output current (defined as the non-linear output of the IC with respect to the transmitted particles) with increasing particle transmission measured by a comparison to the output of the SEM. The latter device is known to be non-saturatable, which can be proven by comparing its output to the signal of the DC-transformer for the stored beam inside the SIS. The number of extracted particles was varied between 2 · 10⁸ and 3 · 10¹⁰ pps by some quadrupoles directly behind the ion source, so that the emittance of the extracted beam from the SIS not influenced. The region, where the IC starts to saturate depends strongly on the applied electric field E_{IC}. Normally we use a field of 2.5 kV/cm. The reason for the saturation is the volume recombination of the created gas-ions and electrons. (The volume recombination depends on the primary ion intensity, while initial recombination does not.) A change of the electric field mainly changes the ion drift velocity u_{ion}^{drif t}, due to u_{ion}^{drif t} \propto E_{IC} [5]. For the distance of 5 mm and 2 kV/cm, this corresponds to a drift velocity of u_{ion}^{drif t} ≃ 0.1 mm/µs and a drift time of about t_{ion}^{drif t} ≃ 30 µs. This also shows, that the IC is not a fast responding detector. The drift velocity of the electrons e_{-}^{drif t} is only weakly dependent on the electric field. In our case it is about u_{e_{-}}^{drif t} ≃ 20 mm/µs resulting in t_{e_{-}}^{drif t} ≃ 0.1 µs.

For the drop down of the efficiency for the 2 kV/cm curve in Fig. 2 at about 10⁹ pps we get a density of the created gas-ions of about n_{ion}^{sat} ≃ 2 · 10⁸ ions/cm³. Due to the faster drift velocity, the electron density is lower, n_{e}^{sat} ≃ 4 · 10⁶ e⁻⁻/cm³. For this non-neglectable charge density volume recombination become important. Taking a rate coefficient of α ≃ 10⁻⁹ cm³/s, the decrease of the measured current with higher charge density can be explained qualitatively. In addition the applied electric field is shielded by the high ion density, which increase the drift time; to include this, self-consistent calculation have to be done.

The deposed dose rate for these parameters is about 30 Gy/s, resulting in a IC current of about 1 µA. Experiments performed with other ion beams yield the same value of the dose rate within a factor of two. Taking pure Ar as the counting gas, did not improve this saturation behavior drastically.

The value of the dose rate at saturation measured here is a factor of 5 lower, than the scaled values determined at BEVALAC, where N₂ was used as the counting gas [2]. But for a comparison it is very important, that all numbers given so far are time-average values. Due to the time structure of the extracted beam (see below), the ion density of the created gas-ions can vary within a factor of 50 in the typical time scale of 100 µs. (This time scale is given by the drift time t_{ion}^{drif t} of the gas-ions.) In addition one has to...
take into account, that the recombination rate scales with the square of the primary ion flux.

4 TIME STRUCTURE OF THE BEAM

With the help of a scintillation counter one can determine the time structure of the extracted beam without any detector inherent time integration. The only limitation is the readout performance of the electronics and the maximum count capability of the detector. Fig. 3 shows the result with a Ne$^{10+}$ 300 MeV/u beam of about $2 \cdot 10^6$ pps. Like expected, the beam is clearly non-uniform, but shows peak-valley variation within a factor of 50 in a time bin of 100 μs. The course of most of the peaks shows a steeper rise than the fall. The behavior of the time signal can partly be explained by recent numerical calculations [11]. In the lower part of Fig. 3 one can see the main Fourier components: Beside the lines at 50 Hz and its lower harmonics, strong lines are located at 300, 600, 900 Hz, dominated by the 1200 Hz line. The width of these lines is about 1 Hz. The reason can be ripples of the synchrotron magnet current, but the higher frequencies were not expected to be so strong. The slow extraction (third order resonance) is very sensitive to any ripple, because this is directly transferred in a tune change, which itself is proportional to the extracted ion rate. These lines are independent of the stored beam current, as a measurement with the cryogenic current comparator shows [12]. More investigations have to be done to understand the behavior and to smooth the extracted ion rate.

5 CONCLUSION

The three presently used detectors can serve as a cheap and reliable standard system for all extracted currents and all species of the heavy ion, high energy beams at SIS. The currents of the IC and SEM differ by three orders of magnitude from fast light ions to slow heavy ions, respectively. The absolute accuracy of the IC is 10 %, the one of the SEM is 20 %; the relative accuracy is much better. Even though there are limits of extracted currents for the scintillators and the ICs, the SEMs can determine the highest possible currents. For higher precision calibrations have to be done. All devices show a good linearity and reproducibility. Other applications, e.g. recording of the spill structure are relatively easy to perform.

6 REFERENCES