DIAGNOSTICS IN HEAVY ION MACHINES

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Abstract

An overview of the measurements of most important beam parameters in heavy ion machines is given. The special characteristics of heavy ions concerning the great variety of parameters with respect to the type of accelerator (linac, circular machine), the species of accelerated ions as well as their energy, beam intensity, beam emittance and time structure are considered. The consequences for the design of beam diagnostic systems are discussed. Typical examples of measuring systems are given. Experimental results taken during the long operating time of the GSI facilities, covering a wide range of parameters, are reported.

1 INTRODUCTION

Due to the large mass, the great variety of isotopes and, especially the large nuclear charge of heavy ions, the lay-out of a beam diagnostic systems may differ considerably from the design for electron or even proton machines. Considering rf-linacs the velocity of accelerated heavy ions will be in general small in comparison to the velocity of light. Therefore, due to the extremely small penetration depth thermal aspects of beam intercepting diagnostic devices become essential. Furthermore, concerning signal calculation for non-destructive pick-ups, the low velocity results in advanced electrical fields, which have to be taken into account designing pick-ups as well as the interpretation of measured signals. In case of circular machines the relativistic mass increase results in an enormous change of revolution frequency and a rather complex relation between rf-frequency and revolution time which may have consequences on the design of diagnostic systems for rings, too. Moreover, depending on the kind of extraction the time structure of the extracted beam can be very different and, considering slow extraction the beam intensity in the external beam lines can be very low. Furthermore, the necessity to separate different charge states and isotopes, generated in the ion sources as well as the need to analyze complex stripper spectra may require special design of diagnostic tools in hard- and software. In the following a short survey on heavy ion beam diagnostics will be presented discussing especially aspects related to the special characteristics of heavy ions. Although contributions are derived mainly from the GSI-facilities, a great variety of heavy ion diagnostics systems has been developed and implemented looking around the laboratories. An review of beam diagnostics in ion linacs is given in [1] and [2].

2 INTENSITY MEASUREMENTS

2.1 Rf-linacs

In most cases heavy ion beams have a time structure with macropulse lengths of some 100 μs up to some ms and a bunch structure, determined by the rather low accelerating rf of some 100 ps up to some ns. Of course, for macropulse currents below some $\mu A's$, Faraday cups are the most frequent used destructive measuring devices. Due to the very small penetration depth of heavy ions in the order of some μm, the heat transfer into cooler regions of the material and, especially to the cooling water may be not fast enough resulting in melting of the cup surface in spite of water-cooling. Some simple formulas for calculation of heat transfer, especially on short time scales are derived in [3].

Above some $\mu A's$ beam transformers offer a non-destructive absolute measurement including monitoring of macropulse shape. The design of beam transformers is discussed in detail for example in [4]. Since sensitivity, resolution, and dynamic range are related to the macropulse length, designing a transformer for heavy ion linacs may require special attention if the macropulse length is in the order of some ms.

2.2 Circular machines

Due to the wide spectrum of ion species and the flexibility of modern machines concerning time structure of the delivered beams, the intensities can be vary from some particles per second (pps) up to about some 10^{12} pps. Figure 1 shows how this wide range of charged particle fluxes can be covered by use of various techniques.

Coming from the very low intensity side, particles can be counted by hitting a scintillation material (plastics, liquids) connected to a photomultiplier. This absolute measurement of particle flux works up to about 10^5 pps using conventional scintillation material in connection with conventional signal processing methods. A very new development is the use of diamond as detector in connection with modern broadband signal processing techniques, extending the range of particle counting more than 2 decades up to some 10^8 pps (see Figure 1). Although the new method of particle counting is described detailed in [5], Figure 2 gives an impression about the capability of the new detector system.

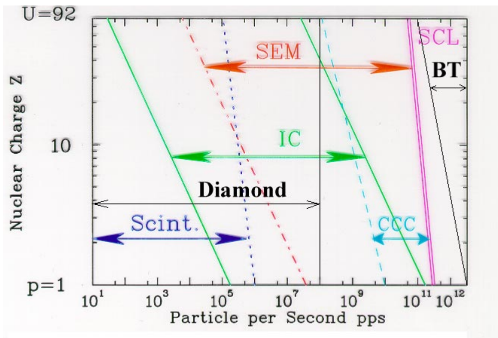

Figure 1: Typical intensity range in the slow extraction mode.

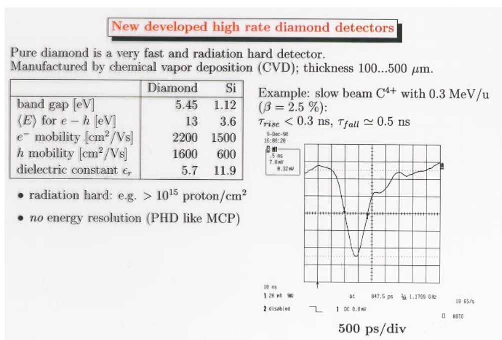

Figure 2: Most important parameters of diamond and silizium detectors and measured output signal.

Since 10^8 pps of for example 50^+ charged heavy ions correspond to a current of only 0.8 nA and conventional beam transformers can be used from some μA upwards it is not possible to cover the whole range shown in Fig. 1 by absolute intensity measurements.The gap is bridged by ionization chambers (IC) and secondary electron monitors (SEM). Calibration of the IC is performed in the overlapping regions with scintillation or diamond counters. Advantageous is a combination of a SEM, an ionization chamber and a scintillation particle counter. Due to saturation of the ionization chambers the SEM, which can be calibrated with the ionization chamber, has to be used at higher intensities. Coming from the high intensity end of Fig. 2 the region of absolute current measurements has been extended downwards by the development of the cryogenic current comparator (CCC) which is described in [6].

2.3 *Identification of isotopes, charge states*

Due to uncontrolled sputtering of materials in an ion source (PIG for example) or an unfavorable selection of the auxiliary gas, strange ions, having nearly the same charge over mass ratio as the required ion may be produced. If an ECR ion source is used to produce metal ions also ions from the material of the oven may be contained in the ion beam. In some cases it may be not possible to separate the isotopes using a magnetic analyzing system. A very typical example is $^{207}Pb^{9+}$ $(A/\zeta = 22.9973)$ and $^{184}W^{8+}$ $(A/\zeta = 22.9939)$ and similar cases are given by the combinations : $^{96}\mathrm{Mo}^{4+}$ and $^{144}\mathrm{Sm}^{6+}$, $^{40}\mathrm{Ar}$ and $^{40}\mathrm{Ca}$, $^{76}\mathrm{Ge}^{4+}$, $^{38}\mathrm{Ar}^{2+}$ and $^{57}\mathrm{Fe}^{3+}$. To analyze the composition of the beam, a set-up based on x-ray spectroscopy may be used [7]. The ions are excited by a thin carbon foil and the emitted radiation is analyzed by a semiconductor detector. Fig. 3 shows an X-ray spectrum of a ^{76}Ge beam with mixtures of ^{38}Ar and ^{57}Fe with a schematic view of the arrangement in the insert.

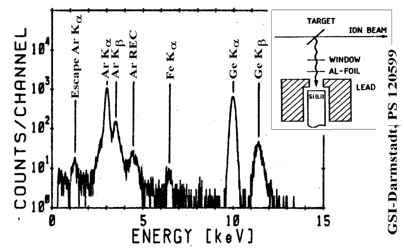

Figure 3: X-ray spectrum of a ^{76}Ge beam with mixtures of ^{38}Ar and ^{57}Fe.

Another typical example is the identification and separation of charge states behind strippers. Figure 4 shows two typical stripper spectra of uranium, demonstrating the efficiency of computer-aided beam diagnostics. In a first step a spline fit is performed to get a mathematical description of all peaks. After that various least squares fits can be applied. Assuming the energy is known, the charge states ζ_i are identified by applying a least squares fit according to:

$$\sum_i \left[B_i - \frac{3.10715 A\beta\gamma}{\rho\zeta_i} \right]^2 = Min$$

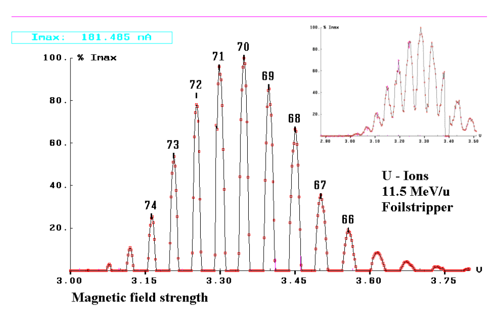

Figure 4: Measured stripper spectra of uranium and charge state identification by least squares fit.

3 BEAM PROFILE MEASUREMENTS

3.1 Rf-linacs

Mostly used devices are profile grids, wire scanners, viewing screens and residual gas ionization monitors. In general viewing screens will stop the particles completely and due to the wide range of intensities, ion species and beam energy, it may become difficult to find the right screen material concerning sensitivity and decay time. Since harps and wire scanners let pass through the main part of the beam they may be more convenient. Using modern signal processing the relation between beam intensity and profile signal will be linear over more than 5 decades. Concerning signal amplification two, in principle different methods have to be considered: Performing current to voltage conversion with a maximum gain in the lowest range of about 2 nA/V or applying the switched integrator principle, where the output voltage is determined by the product of current $times$ integration time. Taking the IC ACF2101 as an example, a charge of Q=10^{-10} As has to be collected to get an output signal of 1 V. Therefore, for a beam pulse length below about 50 ms the I/U-converter principle should be preferred, while in case of long pulses or even DC, the switched integrator gives better performance. Due to the low penetration depth the maximum ratings concerning thermal heating become essential in case of heavy ions. Considering wires made from a tungsten-rhenium alloy the following values have been calculated and confirmed experimentally: The maximum DC, respectively mean beam power should be below 0.25 - 0.5 Watts per mm length of those part of the wire hit by the beam. Considering the pulse power, the energy of one beam pulse should be below the energy needed to melt the so-called range volume, which is given by the penetration depth *times* the area hit by the beam. In case of tungsten this figures out to be 14.5 Ws/mm^3.

The high ionization rate of heavy ions offers the possibility to take advantage of residual gas ionization for beam profile monitoring using the same electronics as for profile grids. Experience at the UNILAC has shown that the expected signal can be calculated within about a factor of 2. Figure 5 shows the calculated maximum signal in the center of the beam in dependence of beam energy for Ne-, Ar-, Xe-, and U-ions taking energy loss data from [8] and [9], assuming 36.5 eV as ionization energy to generate one electron-ion pair in a gas mixture of 80% H_2 and 20% N_2. By designing such a profile monitor, collection of ions should be preferred due to the larger deflection of electrons in the space charge field of moving, non-compensated bunches.

3.2 Circular machines

Non-destructive or even nearly non-destructive methods cannot be applied. Due to the extremely high energy loss of heavy ions even flying wire techniques cannot be used. But taking advantage of the high ionization of heavy ions residual monitors may be an alternative method, [10]. Figure 6 shows the principle of a monitor which is in development at GSI to measure beam profiles in the SIS.

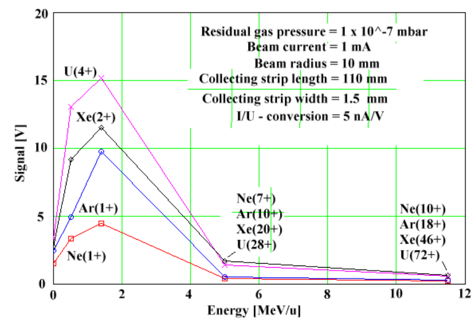

Figure 5: Calculation of signal strengths for detection of H_2-, N_2- ions from residual gas ionization.

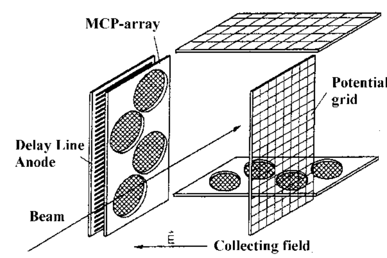

Figure 6: Scheme of a residual gas ionization profile monitor using Multi-Channel-Plates (MCP) for first signal amplification.

Although the residual gas pressure is down to 10^{-11} mbar the MCP's will compensate this by a gain of up to 10^6 and therefore, nearly the same signal strength as given in Fig. 5 can be expected. Of course, beam profile may be measured destructively by use of scrapers.

4 MEASUREMENTS OF PHASE SPACE DISTRIBUTIONS

A review has been given in [11].

4.1 Transverse phase space

The conventional slit-detector method can be modified by using a multi-slit plate in front of a scintillator screen [12], [13], which gives the opportunity to measure the emittance in one transverse phase plane within a single pulse. Taking advantage of modern PC-controlled CCD-cameras a pepper-pot system which gives the intensity distribution even in the 4-dimensional phase space within one pulse has been designed at GSI [14]. Figure 7 shows very first original pictures from the commissioning of the new GSI high current linac. The complex mathematical algorithms to extract emittances from those data are described in [15].

Single shot systems may be the only destructive device to measure emittances in case of high intense heavy ion beams. Furthermore, those systems offer the possibility to study fluctuations of ion sources from pulse to pulse or even within one pulse.

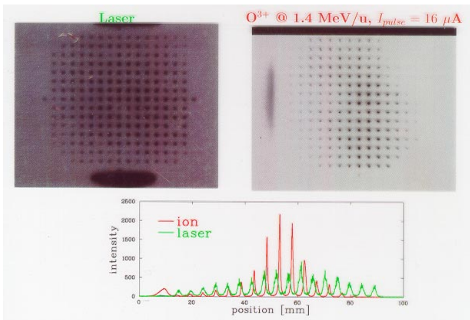

Figure 7: Light spots observed on the viewing screen of a pepper-pot device. Top left: Spots generated for calibration using a laser beam. Top right: Spots from an oxygen beam. Bottom: Intensity distribution along one line.

In case of circular machines transverse emittances can be determined according to the relation between profile width and $\sqrt{\varepsilon\beta}$.

4.2 Longitudinal phase space

There is a great variety of measuring schemes [1], [16]. A set-up using a MCP and diamond counters to measure longitudinal emittances during the commissioning of the new Unilac prestripper is described in [17]. The primary ion beam goes through a thin gold-foil (120 $\mu g/cm^2$). Some particles will be scattered out of the beam by Rutherford scattering which reduces the count rate to a tolerable level. The scattered particles then have to pass two very small apertures. Behind the second aperture a very thin carbon foil is located. The particles passing the carbon foil will generate secondary electrons. The signal is amplified by a MCP and gives a start signal to a TDC (Time to Digital Converter). A second start signal will be generated from the passing particle hitting a diamond counter in some distance behind the carbon foil. Since the stop is always derived from the accelerating rf the method results in a determination of the intensity distribution in the longitudinal phase space.

4.3 Longitudinal bunch shape measurements

The scheme discussed above can be simplified to measure the time structure of bunches with only one diamond counter. Fig. 8 shows the results of a measurement behind the new RFQ of GSI at a final energy of 120 keV/u. Due to the very low velocity of the ions the bunch structure and broadening of the bunch after a drift space observed with the diamond counter cannot be resolved with a capacitive pick-up.

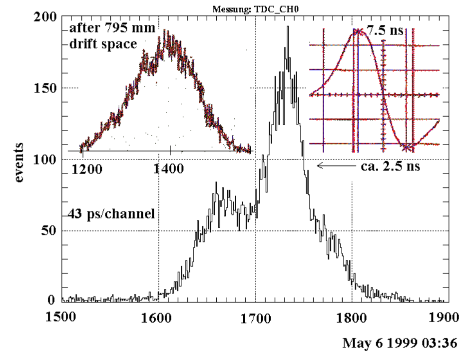

Figure 8: Bunch shape observed with a diamond counter in comparison with the signal of a capacitive pick-up.

Bunch shape monitors based on the analysis of secondary electrons arising from a thin tungsten wire hit by the primary beam have been used successful at various facilities [1]. Considering the maximum ratings with respect to thermal destruction given in section 3.1, this method may fail in case of intense heavy ion beams. Taking over the principle, but detecting electrons from the residual gas ionization a rather complex monitor is in development at GSI [18].

4.4 Measurements of spill micro-structure

Considering heavy ion synchrotrons in slow extraction mode, measurement of spill structure becomes important. Due to the very low ratio between typical revolution times in the μs - region and spill times up to some seconds the intensity of the extracted beam may cover the whole range shown in Fig. 1.Therefore, the measuring system has to be designed very carefully with respect to sensitivity and bandwidth. Figure 9 shows an example [6] from the SIS, measured with the cryogenic current comparator (CCC in Fig. 1). Although the time average over the spill is only

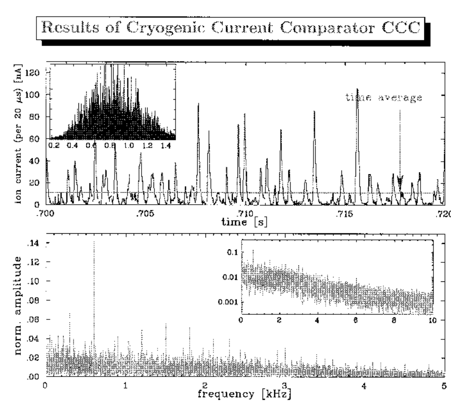

Figure 9: Measurement of spill micro-structure with the CCC.

about 10 nA, peak currents in the order of 100 nA and gaps of some 100 μs have been observed. Of course, the ratio peak to average depends on the integration time (bandwidth) of the measuring system and, in case of SIS, can be improved considerably if the rf-voltage of the accelerating cavity remains on during the flat-top.

5 BPM-SIGNAL PROCESSING

As already mentioned in the introduction, measuring systems in heavy ion synchrotrons differ from e-, p-machines due to the large change of frequency during acceleration. Therefore, considering broadband systems with the possibility to monitor single bunches at a determined time and a selected BPM, the large change of velocity has to be taken into account. At the SIS this has been realized by a so-called timing generator [19], which produces rf-synchronous gate pulses using a fast RAM-table, whereby addressing is performed by an rf-related clock frequency. Of course, this can be realized now by use of modern DSP's. Due to the wide range of different particles resulting in a wide range of intensities and the large change of the geometric bunchlength during acceleration, a broadband signal processing system for heavy ion machines has to cover a larger dynamic range compared to e-, p-machines. In case of the SIS the total dynamic range covers 140 dB (-80 dBm+60 dBm). The advantage of single bunch observation is demonstrated in Fig. 10.

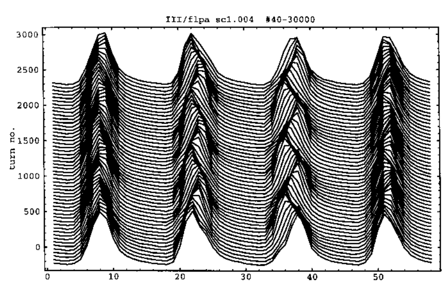

Figure 10: Bunch oscillations observed with a broadband system at flattop of SIS.

Considering narrowband systems, the large change of frequency range can be covered by use of modern phase locked loops and mixing the frequency-swept bunch signal into constant intermediate frequency signals which then can be amplified with a determined bandwidth. Of course, in comparison to the broadband system the sensitivity increases depending on the selected bandwidth. Figure 11 gives the SIS-BPM sensitivity versus resolution bandwidth [20], which holds for all similar BPM systems.

6 REFERENCES

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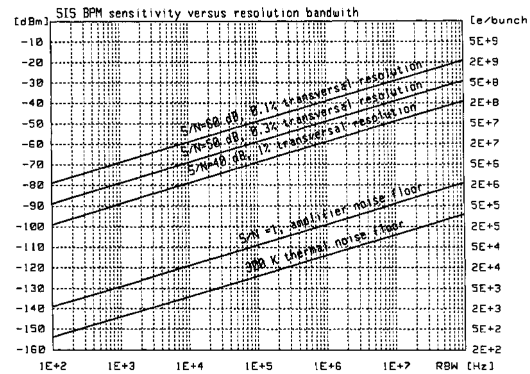

Figure 11: Sensitivity of narrowband systems versus resolution bandwidth.

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