Methods of Beam Profile Measurements at High Current Hadron Accelerators

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Abstract. The precise determination of the transverse beam profile is an important issue for the operation and the development of any accelerator facility. At hadron LINACs the application of traditional intersecting methods, like wire scanners and SEM-grids, are restricted by the high current and the related risk of material melting. At synchrotrons non-destructive methods are favored to monitor the properties of the circulating beam. Recent developments and technical challenges for the non-destructive devices Beam Induced Fluorescence (BIF) Monitors and Ionization Profile Monitors (IPM) are described.

DEMANDS FOR BEAM DIAGNOSTICS

High current proton and ion accelerators are under operation or development to achieve highest possible beam brilliance. Beam diagnostics is an integral part of determining proper settings of all active components to ensure emittance conservation. General demands for any diagnostics are:

- The devices shall work non-destructively to measure even beams of highest power which destroy every intersecting material.
- In order to monitor the undisturbed properties of a beam stored in a synchrotron at any time during the cycle, the diagnostics must be non-intersecting.
- The length of diagnostics mechanics in beam direction shall be small in order to use nearly 100% space for accelerating and focusing elements.
- The diagnostic devices shall have a large resistance against radiation defects caused by beam irradiation.
- Technical realizations shall benefit from commercially available solutions to save man-power and cost during the development phase.

One important parameter is the transverse profile, which must be controlled to achieve optimal matching between different acceleration structures. At many LINACs and synchrotrons wire scanners are used as a standard for profile determination. They offer high spatial resolution down to 20 μm as given by the wire diameter. They have a very large dynamic range and beam halo contribution can be determined. SEM-grids, made of a ~1 mm spaced wire or ribbon array are popular, but here the spatial resolution is limited. Both methods are destructive and the device might be destroyed by the high beam power.

Two types of non-destructive methods are described here, based on atomic collisions between the beam ions and the residual gas. These methods are: The detection of single photons from excited levels of the residual gas atoms or molecules by Beam Induced Fluorescence (BIF) and the direct detection of ionized residual gas ions or electrons at an Ionization Profile Monitor (IPM).

BEAM INDUCED FLUORESCENCE

In most LINACs N₂ dominates the residual gas composition. Due to the electronic stopping power the molecules are ionized and after the primary collision left in an excited state. A strong fluorescence in the blue wavelength range 390 nm < λ < 470 nm is generated by a transition band to the N₂⁺ electronic ground state (B²Σ⁺ₓ → X²Σ⁺_g + γ), having a lifetime of about 60 ns [1]. Tests with other gases e.g. Xe were performed, but in this case a lower photon yield in the optical wavelength range was reported [2]. The low amounts of photons can be detected and amplified using an image intensifier. This commercially available device consists of a photo cathode to transform the photons into electrons, which are then amplified by a spatial resolving MCP electron multiplier. It is followed by a phosphor screen to create again photons, which are finally monitored by a CCD camera. A single primary photon can be amplified to yield 10⁴ to 10⁷ detectable photons on the CCD. The amplification factor depends on the MCP type installed in the image intensifier. The hardware set-up, as used for tests at GSI, is displayed in Fig. 1.
FIGURE 1. The installation of an image intensifier at GSI [5].

The BIF-method was pioneered at Los Alamos LINACs [3] for protons at MeV energies to monitor the profiles non-destructively for high power dc-beams.

Example for BIF at a pulsed LINAC

The GSI UNILAC is a pulsed heavy ion LINAC with a macro pulse length of about 100 μs to fill the following synchrotron. The beam profile should be monitored within a single macro pulse; therefore the use of a long integration time for an improved signal-to-noise ratio is impossible. Due to the low amount of emitted photons during typically 100 μs integration time, a large amplification of $10^6$ is required by using a double MCP in s.c. Chevron geometry inside the image intensifier [4]. A raw image is displayed in Fig. 2 together with the transverse profile as yielded from the projection along the beam path [5]. The correspondence of the measured profile to other methods is excellent.

Each of the light spots on the raw image is created by one single photon. Due to the statistical nature of the signal generation, the data quality can be enhanced by data binning or by averaging several images. The resolution of 300 μm/pixel is sufficient for the displayed parameters. A higher resolution can be reached by varying the distance between the beam pass and the camera or by a proper choice of the optics. This flexible adaption for higher resolution is only limited by the required focal depth for an accurate mapping. By using a regulated gas valve the pressure could be locally (within 1 m) raised up to $10^{-4}$ mbar. The pressure bump does not have a measurable influence on the ion beam delivered to the GSI synchrotron.

An advanced application is the determination of a possible variation of the beam profile during the macro pulse, as shown in Fig. 3. The fast switching of the voltage between the photo-cathode and the MCP within 100 ns can be used to restrict the exposure time. For the case of Fig. 3 one image of 40 μs exposure time is recorded and the measurement is repeated with 8 different trigger delays. This type of measurement is not possible with an intersecting SEM-grid due to the risk of wire melting by the large beam power.

At the GSI test set-up an 8 bit CCD camera with a maximum of 80 frames per second at 658 x 494 pixels was chosen. The CCD signals are directly digital-converted at the camera head and transferred using Firewire IEEE 1394 protocol [6]. Compared to an analogue video link, no signal degradation due to long cables occurs. The Firewire bus standard allows a maximum data rate of 400 Mb/s which is equal to 100 frames per second at VGA resolution. The variable bus architecture with up to 63 nodes is well suited for the distributed diagnostic installations in the various beam lines. The data acquisition and evaluation is performed with modern commercial hard- and software systems.

FIGURE 2. Image of a 200 μs U$^{28+}$ beam with I=700 μA recorded during one UNILAC macro-pulse with a vacuum pressure of about $10^{-5}$ mbar. The two dimensional image from the intensifier (left) and the projection for the vertical beam profile (right) are shown [5].

FIGURE 3. The determination of the width variation during a macro-pulse is shown. The lower graph compares the normalized image intensity with the measured beam current [5].
Example for BIF at Synchrotrons

Careful investigations have been performed at the PS-Booster and the PS at CERN for proton beams [2]. Here the wavelength spectrum and photon yield was measured on a wide scale of beam energies from 50 MeV up to 25 GeV. For N₂ pressure bump the wavelength spectrum is comparable to the results obtained for proton collisions at 100 keV [1]. The lifetime of the excited states was determined using a circulating ~ 5 ns long bunch at 25 GeV energy and observing the decay time using a photomultiplier. The result of \( \tau = 58.0(3) \) ns coincides with the one recorded for 100 keV. The absolute photon yield in the optical wavelength range is equivalent to an energy loss (electronic stopping power) of about 3.6 keV in N₂. Tests with other gases did not result in a larger photon yield.

A BIF monitor was successfully installed at the CERN-SPS [7]. For a pressure bump of N₂ in the order of \( 10^{-7} \) mbar profiles within 20 ms integration time, corresponding to about 900 turns, were recorded with sufficient statistical accuracy. A comparison with the standard flying wire scanner method is shown in Fig. 4, proving the applicability of this method also at high energy synchrotrons.

The fast extracted beam can also be monitored at an external beam tube, as demonstrated at COSY [8].

Example for BIF at ion sources

Behind proton sources, where the protons are only accelerated by the ~ 100 kV potential of the ion source platform these types of measurement are performed in several labs, e.g. [9, 10]. The light yield is large and a long integration time enables careful investigations concerning possible signal broadening processes. A comparison of different gases shows a good correspondence, as displayed in Fig. 5. Taking the different excited levels and lifetimes into account, this result is not evident. But a broadening, in particular at the beam edges was reported [9], therefore the wavelength spectra with varying angles to the beam axis were measured. Due to the angle-dependent Doppler-shift, the fluorescence originating from the residual gas (nearly at rest) and light emitted by the beam particles can be discriminated. The Balmer H\(_\alpha\) line, emitted by the beam protons via recombination \( p + e^- \rightarrow H^0 + \gamma \) was detected, as well as lines from neutral and charged hydrogen molecules (H\(_2\), H\(_3^+\), H\(_4^+\)). The contribution at the beam edges originates mainly from these lines. It can be concluded that the applicability of the BIF method has to be carefully checked to prevent misinterpretation due to the complex processes and large residual gas densities close to an ion source. This problem probably does not appear behind a LINAC due to a single composition of beam ions and the low cross section for electron capture.

FIGURE 4. Comparison of the normalized vertical profile width as determined by the BIF-method and a flying wire scanner at CERN-SPS [7].

IONIZATION PROFILE MONITOR

In most synchrotrons and storage rings the transverse profile of the circulating beam is monitored by detecting the ionization products from the interaction of the ion beam with the residual gas molecules (mainly H\(_2\)), as shown schematically in Fig. 6. Inside the vacuum tube biased electrodes produce an electric field of typically 50 V/mm to accelerate the secondary electrons or ions toward an MCP. Here they are amplified by a double MCP, each particle hit yields about \( 10^6 \) electrons. Two different anode readout technologies for the amplified signal are commonly in use:

- **Phosphor screen:** The electrons create light spots on a phosphor screen behind the MCP, which are monitored by a CCD camera, as shown schematically in Fig. 6. A high spatial resolution can be achieved with this readout method, only limited by the ~ 30 \( \mu m \) granularity of the Chevron-MCP chan-
nels. Therefore this method is preferred in cooler rings. A typical time resolution is in the order of 10 ms, given by the frame rate of the CCD camera. For a turn-by-turn readout on a μs time scale the CCD camera is too slow. A multi-anode photomultiplier [11] or a photo-diode array [12] has to be installed as a second readout system.

- **Wire array:** An array of wires can be mounted behind the MCP to collect the current of amplified electrons; a technical realization is shown in Fig. 7. The spatial resolution down to 0.5 mm, as given by the distance of the anode wires, is less than for the phosphor screen readout. But it is possible to get a time resolution of ~10 ns using sensitive broadband rf-amplifiers [13].

For beam currents as normally stored in high power synchrotrons, the space-charge field \( E_{SC} \) of the beam is comparable to the IPM electric field. To overcome the influence of \( E_{SC} \) the electrons are guided towards the MCP by a magnetic field of typically \( B = 100 \) mT. This value is chosen so that the cyclotron radius \( r_c \) along a field line is comparable to the resolution of the MCP. The cyclotron radius \( r_c = m_e v_{\perp} / eB \) is mostly determined by the initial electron velocity \( v_{\perp} \) perpendicular to the \( B \)-field after the atomic collision. It can be estimated that 90% of these electrons are emitted with kinetic energies below 50 eV, resulting in \( r_c < 100 \) μm. A well-defined \( B \)-field uniformity is required along the full path of the secondary electrons for the interaction point to the MCP (up to 100 mm) to yield an undistorted image of the beam. Different designs have been realized, using either electro-magnets [11] or permanent magnets [13, 14].

To estimate the possible distortion due to the beam space-charge (via \( E_{SC} \times B \)-drift) and the residual \( B \)-field non-uniformity, numerical calculations of the electron trajectories are required.

With an IPM the transverse profile can be monitored without an influence on the beam. One important application is the alignment of the electron- or stochastic cooling process [15]. As displayed in Fig. 8, electron cooling is applied to stack the beam via iterative injections. Other

applications are the monitoring of the beam behavior during emittance blow-up due to intra beam scattering, necessary crossing of tune resonances or a horizontal-vertical coupling due to skew quadruples. For these processes significant changes of the transverse profile are slow compared to the revolution period (typically 1 µs to 100 µs), therefore a time resolution of ms is sufficient and the transverse profile can be averaged over many turns. The high spatial readout technology by a phosphor screen anode and a CCD camera is well suited for this application.

But there are also fast processes, which must be monitored on a turn-by-turn basis [11, 13, 14]. An example is the control of the injection matching into a synchrotron as displayed in Fig. 9. If the orientation of the transverse emittance or the value of the dispersion of the injected beam (as given by the transfer beam line setting) does not correspond to the values at the synchrotron injection point, coherent transverse beam oscillations occur leading to an emittance blow-up of the stored beam. A matched setting of the transfer line lattice, controlled by the non-destructive IPM, is required to achieve high brilliant beams.

COMPARISON BETWEEN BIF AND IPM

The BIF-method detects photons and no mechanical installation inside the vacuum tube is required. Commercial image intensifiers are available, and commercial data acquisition and evaluation systems can be used, reducing the amount of human resources during the development phase. The spatial resolution as given by the optical magnification of the lens system can easily be matched to the application. At LINACs the residual gas density is relatively large and therefore the amount of detectable photons is higher than at synchrotrons. But compared to the detection of ionization products the photon yield is reduced by at least one order of magnitude because particular levels have to be excited for the emission in the optical range. Only those photons, which are emitted toward the camera can be detected, resulting in a solid angle of only ΔΩ ~ 10^-4. A further reduction is required by a limited iris setting of the optics to ensure a sufficient focal-depth.

The IPM detects all charged residual gas particles due to the applied electric field, but a complex and expensive installation inside the vacuum tube is required. For intense beams a magnetic field must guide the residual gas electrons toward the MCP. Its design might be a challenge due to the uniformity requirement and the anomalous large clearance (up to 40 cm). The spatial resolution of ~ 100 µm is sufficient for most applications at a synchrotron.

REFERENCES

8. J. Dietrich et al., these proceedings.