BEAM DIAGNOSTICS, OLD AND NEW*

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Abstract

The performance of accelerators and storage rings depends critically on the completeness and quality of their beam diagnostic systems. It is essential to equip them from inception with all the instruments providing the information on the properties and the behaviour of the beams, needed during running-in, in operation, and for development of performance towards the design goal and often well beyond. Most of the instruments have proven their worth since decades, but their power has been increased through the modern means of data acquisition and treatment. A few new instruments have made their appearance in recent years, some still under development and scrutiny for their operational value and precision. The multi-accelerator chains of today's and tomorrow's big colliders have tight tolerances on beam loss and emittance blow-up. For beam diagnostics this means a great challenge for precision and consistency of measurements all along the chain.

1 INTRODUCTORY REMARKS

Despite an all-encompassing title, evidently not all areas of beam diagnostics can be covered. Specialities like instrumentation for linear colliders, feedback-damping, beam-loss monitoring, collider luminosity measurement and ultra-fast bunch length measurement, must be left aside here. Excellent presentations were given on these subjects at recent conferences. Also, repetition of what was offered in similar review talks will be avoided.

On the other hand, some weight will be given to the diagnostics aspect of CERN's accelerator chain for the future Large Hadron Collider (LHC), and rather than giving detailed descriptions of systems and the results obtained with them, trends of evolution, challenges and open needs will be pointed out.

2 SOME EVERGREENS

It is quite amazing to see many tools of beam diagnostics of a venerable age of many decades, and even up to a century, around accelerators built with the most modern technologies. For example, Röntgen saw the first X-ray images in 1895 on luminescent screens, and still today these are one of the most basic and popular beam diagnostic means, although now more correctly called scintillator screens.

Other examples are: the Faraday-cup, to measure current or charge of beams delivered by low energy accelerators, such as RFQs; the "pepper-pot", which was the first crude instrument for measuring emittance, also limited to low energy beams; the ionization chamber, still an appreciated means for sensitive detection of beam loss and radiation levels; secondary emission detectors in a great variety of constellations; and so on.

All these venerable detectors have undergone considerable evolution in many aspects, such as resolution, both temporal and spatial, dynamic range and sensitivity. The most remarkable advance came with the advent of digital data acquisition and treatment: with its help one can draw rather precise quantitative data from instruments which previously offered only qualitative information.

We shall mention two examples of aged instruments rejuvenated in this way: the scintillator screen and the pepper-pot.

Scintillator screens are inserted into the path of the beam by a remotely controlled mechanism. The light which is produced when the beam particles strike the screen is observed with a TV camera. The screen may have a graticule, made visible by external illumination (Fig. 1).

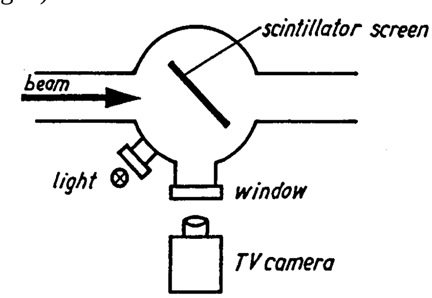

Figure 1: Typical arrangement for observation of beam position and size with a scintillator screen and a TV camera [1].

The light spot observed on a remote monitor permits rather accurate determination of beam position, to 0.5 mm under favourable conditions. One only gets a rough impression of the beam size, because the commonly used systems are driven into saturation, such that on a dark background one only sees a rather uniform white spot, the size of which depends on beam intensity and various equipment settings.

A modern version [2] will use a CCD-camera for good linearity, digital data acquisition (a "frame grabber") and treatment such that a 2-dimensional density distribution can be derived (Fig.2).

* This is essentially a repeat of "Beam Diagnostics Revisited", invited talk given at EPAC, Stockholm, June 1998.

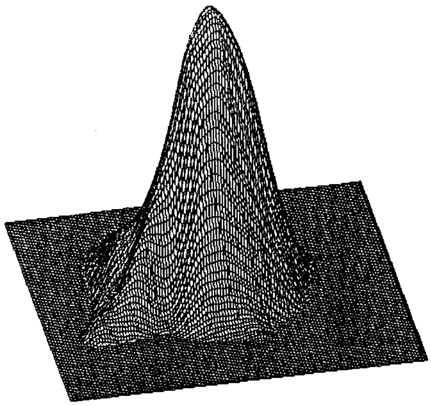

Figure 2: 2-dimensional beam density distribution derived from the light-spot on a scintillator screen [3].

The pepper-pot, as its name suggests, is a metal plate with small holes in it. The plate is thick enough to stop the low-energy beam that one is measuring. The particles that pass through the holes are left to diverge over a drift-space, so that when they strike a scintillator screen they form elongated images (Fig.3). The position of the holes determines the coordinates of the particles and the elongations are a measure for the divergence at those coordinates, so that with the help of a ruler and a slide-rule one quickly obtained a good estimate of the beam's emittance.

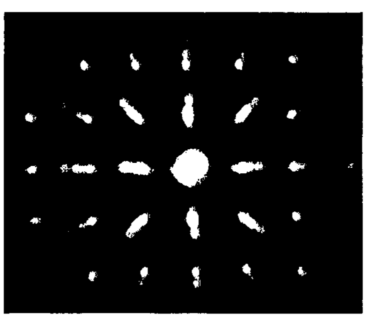

Figure 3: The particles passing through the holes of a pepper-pot and a drift space form elongated images on a scintillator screen [4].

Modern digital techniques have brought about a come-back of this old-fashioned device and turned it into a convenient real-time and fairly accurate instru-ment. It is used, e.g., at the Heavy Ion Linac of the CERN PS Complex, for Pb^{27+} ions at 4.2 MeV/u [5]; at the LASER Ion Source, being developed for the same linac [6]; and a further system has become available at GSI, Darmstadt, for 1.4 MeV/u Uranium ions [7].

3 SOME NOVELTIES

A full and fair account of "novelties" is impossible to give. The criterion for what constitutes a novelty is rather fuzzy, as the basic idea may have been around for many years, until someone, perhaps driven by a particular need, picked it up and brought it to fruition. Rather than attempt to give a complete list, a quite subjective selection of devices and methods shall serve as illustration that beam diagnostics is an innovative and prospering branch of accelerator physics.

Over the last few years a most useful tool for RFQs and linacs was brought to operational perfection, the principle of which was proposed and a first-generation version built some two decades ago [8]: the Bunch-Length Detector (BLD), and several variants of it [9]. The secondary electrons emitted from a thin wire, placed in the beam, are accelerated towards a transverse deflector driven by the linac RF. The density distribution of the secondary electrons in the detector plane is then an image of the longitudinal density distribution of the beam particles in a linac bunch (Fig.4). By scanning the wire through the beam, the complete 3-dimensional bunch density distribution can be determined. This is a great step forward in understanding the effects of the linac's parameters and bringing the linac to high performance.

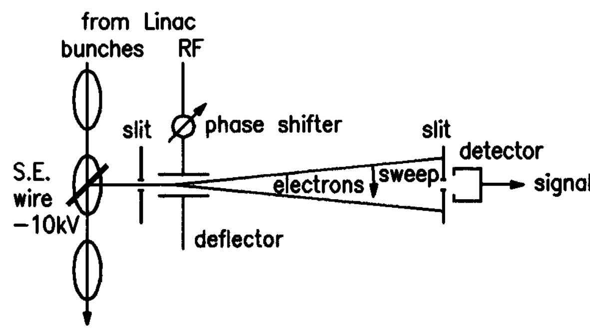

Figure 4: Basic layout of a Bunch Length Detector (BLD, according to [9]).

Optical Transition Radiation (OTR) increasingly replaces scintillation as a means of observing beam position and size in transfer lines [10]. OTR screens can be made very much thinner than scintillator screens, so that the effects on the beam, energy-loss and multiple Coulomb scattering causing emittance blow-up, are much weaker. Moreover, they do not suffer from two limitations of scintillator screens, namely saturation and propagation of light within the screen.

One of the nearly-non-destructive means to measure profiles of circulating beams is the fast wire-scanner, brought to a high degree of perfection in recent years. The increase of speed to 20 m/s, made possible through real-time controlled optimized movement, minimizes the blow-up caused to the beam, together with the use of thin strands of carbon fibres (instead of W-, Ti- or Be-wires), which also greatly improved the lifetime. The fast wire-scanners in the CERN 26 GeV PS [11,12] cause hardly any blow-up in a single sweep at an injection energy of 1 GeV, and have been demonstrated to perform well in the preceding Booster down to its injection energy of 50

MeV, although causing significant blow-up at such a low energy.

Another detector that has a long history before it came to practical fruition recently, is the Cryogenic Current Comparator [13]. Essentially a variant of the dc beam current transformer, using a superconducting transducer and a SQUID, it pushes the sensitivity up by 3 orders of magnitude. Despite a considerably greater technological complication, a typical resolution of 1 nA makes it the ideal tool for measuring the low intensities of slow extracted beams from ion accelerators, including those for medical application.

A particularly powerful means available to accelerator physics is the “Schottky scan”, the paragon of non-invasive diagnostics. It is based on the granu-larity in the density distribution of circulating beams, which produces beam-induced noise in specially built, highly sensitive, pick-ups. This “Schottky noise” consists of the harmonics of the revolution frequency, nf_{rev}, and, when the pick-up is position-sensitive, the “betatron sidebands”, $(m\pm Q)f_{rev}$. Signal analysis with scanning frequency analyzers has led to the term “Schottky scan”. First applied to a particle beam in 1972 at the CERN ISR [14], diagnosis based on Schottky signals has undergone a spectacular evolution, profitting from technological advances in low-noise amplifiers, special pick-up structures and digital signal processing (FFT). It has become one of the most refined means of measuring beam and machine properties, as varied as beam intensity, frequency and momentum spread, Q-values and chromaticity, rms betatron amplitude and emittance. For the measurement of intensity, they are first calibrated against a beam current transformer and can then extend the measurement to very low intensities. The record resolution was achieved at the Initial Cooling Experiment (ICE) at CERN, where a beam was measured to consist of 80 ± 13 antiprotons. Schottky scans take time and are therefore mostly used at storage rings. Since one observes incoherent signals, scans are mostly made on coasting beams, but with the necessary precautions, bunched beams can be observed too [15].

One can often not distinguish between a novel detector and a novel method of using existing detectors. As an example, let us look at the verification of betatron matching upon injection into a circular accelerator. Incorrect matching will lead to coherent quadrupole oscillations, i.e. a beating of the beam width, until decoherence turns them into an emittance increase. One of the devices capable of detecting beam-width-beating is the quadrupole pick-up, which can sense variations of the ellipticity of beam cross section. However, information on ellipticity is easily swamped by the common-mode signal when the beam is not perfectly centred in the pick-up. It took the development of a new way of treating the signals from the four electrodes to permit practical use [16], but very good centring of the beam is still a prerequisite.

A further method for observation of the coherent variation of beam size was proposed [17]. At high energies, one can insert a screen (scintillator or OTR), in the path of the beam and, with digital image acquisition and treatment, derive beam width turn-by-turn. A gradual increase in width, due to multiple Coulomb scattering, will be superimposed. Similarly, a secondary emission grid can be used [18], (Fig. 5).

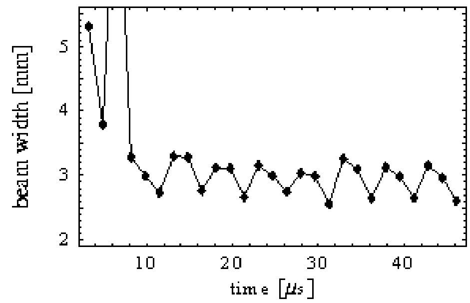

Figure 5: Periodic variation of beam width (σ) following mismatched injection. From multi-traversals of 50 MeV protons through a low-mass secondary emission grid in the CERN PS Booster. The initial transients are an inherent consequence of the multiturn injection process. Betatron tune Q = 4.34 [27].

The development of position pick-ups to unpre-cedented resolution has brought a new impetus to the time-honoured method of variation of quadrupole currents. In fact, the precision alignment of CERN's LEP and of other machines is obtained using "k-modulation" [19]. This, together with modern means of controls and on-line optics calculation, has also returned respectability to its application in transfer lines, where it allows economically, and without doubts about relative alignment, the determination of whether a beam passes through the centre of a quadrupole or how far off it is. In other words, every quadrupole can serve as a position detector.

4 SOME CHALLENGES

Apart from the instrumentation for linear colliders, the greatest challenge is precise and coherent measurement of beam parameters throughout the long chains of accelerators in today's and tomorrow's big circular hadron colliders, in which no synchrotron radiation damping covers up the imperfections of beam-handling at all stages. Foremost amongst these parameters is transverse emittance. Witness to the importance of this subject is the fact that an ICFA Workshop was recently dedicated to it [20].

There are several reasons for this being a challenge. Emittance is measured at the various stages with instruments of quite different nature. Let us take as an example the injector chain of the future LHC. At the RFQ and the 50 MeV linac one uses instruments basically resembling the pepper-pot, and another one is derived from the above-mentioned BLD. Secondary Emission Monitors (SEM-grids) measure the profiles on the way to and into the 1 GeV Booster. When the beam circulates there, it is measured with a fast wire-scanner, which measures projected density distribution, and, in a destructive way, with the BEAMSCOPE [21], which really measures amplitude distribution. On the way to the 26 GeV PS, there are again SEM-grids, and on the beam circulating in it again a fast wire-scanner and partially destructive measurement targets, indicating amplitude distribution. SEM-grids provide quality checks after ejection from the PS and upon injection into the SPS. At that machine, it is foreseen to add OTR screens with quantitive evaluation for profile measurements at injection and at ejection towards the LHC, where again a panoply of different instruments will measure profiles.

Measuring profiles is one thing, obtaining emittance is another. In a circular machine one must know accurately the value of the beta-function. In transfer lines, where emittance is calculated from several profiles, one must know equally accurately the transfer matrices between the usual 3 SEM-grids or screens. And all of this is only valid when there is no coupling.

The density profiles obtained from such basically different instruments, and the emittances derived from them, must be treated mathematically such that a valid comparison can be made. This is no mean task when one aims at an absolute precision of typically 5% in emittance, i.e. 2.5 % in beam "size". The definition of size is a further difficulty in obtaining coherence of data. A beam never has a Gaussian distribution and the way this fact is dealt with mathematically is often a matter of ideology. Suffice it to say that definition and treatment should be representative for the bulk of the beam when the final concern is collider luminosity [21, 22, 23].

One challenge that stands out is the development of a detector which, in machines like PS, SPS and LHC, measures the profile of the beam during acceleration in a non-destructive and continuous way, with a precision of the order of 0.1 mm in the PS, demanded for beams

destined for the LHC.

Synchrotron light and Compton scattering, so successfully used on electrons and positrons, are not accessible. The one instrument that comes close is the residual gas monitor, in which electrons and/or ions, created in the residual gas through the ionizing action of the beam, are extracted with electric fields and used for imaging the beam density profile. However, to obtain a sufficient spatial resolution, one would need to use very high electric fields and a strong focussing magnetic field in the same direction. These perturb the beam and must be compensated, so that it becomes an altogether very voluminous and clumsy apparatus.

Two lines may be pursued. The one is using the light emitted from the residual gas produced by the excitation of its atoms through the beam particles. Attempts at using this method have been made in the past [24, 25], and showed a number of perturbing effects. Still, a new look at it is worth the effort. The other is based on the deflection suffered by a thin ion-beam, swept transversely across the circulating beam, in the latter's electric and magnetic field. Promising experiments were made [27].

5 CONCLUDING SERMON

When setting about conceiving diagnostic systems for an accelerator, one should first thoroughly acquaint oneself with the machine and all possible modes of operation and with the properties and behaviour of the beams under various conditions. That is, not only the nominal beam, but also as it may be at an early stage of running-in and under abnormal conditions, when one particularly depends on diagnostics. One will aim for easily perceived information for routine operation, and will provide for the special needs of accelerator physics experiments.

When making the detailed design of an accelerator, diagnostics is to be included at an early stage: for the trivial reason that space must be foreseen for the detectors, but also because the capabilities of the diagnostic systems, and the information they deliver, can have repercussions on the design of the accelerator (e.g. through the possibilities offered by feedback systems).

Accelerators ought to be equipped with a complete set of diagnostics from the day of first beam, as it is during the running-in that it is dearly needed. However, one must be aware of the fact that also the diagnostic systems need their own running-in, with beam.

For each diagnostic system there should be an expert who sees it as a whole, from the detector in the tunnel, through the electronics, data acquisition and treatment, to the display in the control room. Otherwise, efficiency of use suffers and unnecessary complication is added.

Finally, on-line calibration, on user-request or automatic, during routine operation, is needed for always correct results and to instill the users with confidence.

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