HIGH RESOLUTION TRANSVERSE PROFILE MEASUREMENT

E. Bravin, CERN, Geneva, Switzerland

Abstract

The performance of a particle accelerator is in large part defined by the transverse emittance of the beams. In most cases, like colliders and light sources (Synchrotrons or Free Electron Lasers), the quality of the final product, i.e. luminosity and brilliance, is directly linked to this parameter. For this reason many techniques and devices have been developed over the years for monitoring the transverse distribution of particles along accelerator chains or over machine cycles. Moreover modern designs of accelerators allow smaller size and/or higher current beams. New, more demanding, emittance measurement techniques have to be introduced and existing ones expanded. This presentation will review the different methods and the different instruments developed so far.

WHY HIGH RESOLUTION

There are many reasons why measuring the transverse profiles with high resolution is important, among these are:

- Emittance preservation: particularly important for hadron colliders and linear colliders as there is no synchrotron radiation damping in these machines. Usually particles are accelerated from a source through several linear and circular machines before entering in collision. Emittance blow-up happening at any point in the chain is maintained and amplified. In order to minimize this effect instruments for measuring the emittance at each stage are necessary. Additionally, in the case of circular colliders, the beams are maintained in coasting for several hours, without particular care transverse blow-up would reduce the luminosity. Table 1 presents the emittance budget of the LHC injection system as an example.
- Luminosity maximization: The other important factor in the maximization of the luminosity of a collider is the optimization of the optical functions at the IP. Where possible this is made by directly measuring the beam sizes at the interaction point, otherwise the size has to be calculated using the measured emittances and the calculated/measured optical functions. In the cases where the beam size at the IP can not be directly measured redundant beam profile monitors at different positions in the ring are essential as was for example observed during the LEP operation. Table 2 presents the values of the transverse beam sizes for a relevant sample of different machines.
- Beam loss reduction: another interesting subject in accelerators development is the design of ever more intense "drivers" machine, used to generate very intense particles beams at relatively low energies. This is the case of neutrino factories and neutron spallation sources for example. In these machines

even small beam losses, in terms of the fraction of the beam lost, have serious consequences as they can damage the components of the machine or create activation making interventions very difficult. The formation of a halo around the core of the beam is an important process and need to be minimized. For the monitoring of the halo the relevant resolution is more in the measurement of the intensity than on the position.
- Development of new machines: Beside several new accelerators currently being built, LHC, FLASH, LCLS, FERMI etc. there are parallel ongoing studies and developments for the next generation of accelerators. Here beams of smaller and smaller emittances are generated and need to be measured in order to tune the machine and demonstrate the quality of the results.

Table 1: Emittance budget for the LHC injector chain

	E_k [GeV]	ε^* [π μm]	σ [mm]
LINAC	0.0001 – 0.05	~1.0	
BOOSTER	0.05 – 1.4	2.5	0.3 – 6.5
PS	1.4 - 26	3.0	0.3 – 15
SPS	26 - 450	3.5	0.1 – 6
LHC	450 - 7000	3.7	0.1 - 2

Table 2: Beam sizes at the IP for a selection of accelerators

	σ_x [μm]	σ_y [μm]
Tevatron	30	30
LHC	16	16
PEP-II	200	7
SLC	1.5	0.65
ILC	0.6	0.006
CLIC	0.043	0.001

TYPES OF PROFILE MONITORS

Profile monitors can be divided in two families: those for circular machines and those for linear machines and transfer lines.

In the first family there are:
- Fast(er) wire scanners
- Laser wire scanners
- Synchrotron light monitors
- Rest gas ionization

And in the second:
- Slow(er) wire scanners
- Laser wire scanners
- Imaging (scintillators / OTR)
- Wire grids (harps)

The main differences between the two families are dictated by the different beam passage frequencies, in the

Beam Instrumentation and Feedback

Profile and Transverse

order of hundreds of Hertz maximum for the linacs and mega Hertz for circular machines.

WIRE SCANNERS

Wire scanners are among the most used instruments for the measurement of the transverse profiles. The principle is quite simple and consists in scanning a thin wire across the particle beam while measuring the intensity of the interaction between the wire and the beam. Two different detection systems are normally used. The first consists in detecting the flux of secondary high energy particles generated by the interaction of the beam with the nucleus of the wire; this system requires a particle detector downstream of the wire scanner, usually a scintillator-photomultiplier system. The other method is based on the detection of the electric current induced on the wire by the secondary emission of electrons. Both systems provide a signal proportional to the number of particles interacting with the wire, by plotting this signal as function of the wire position the profile is obtained.

Wire scanners can have a linear or a rotative movement, the first is more precise but is limited in speed (max. 1m/s), the second can achieve higher speeds (up to 20m/s)[1] but has a reduced resolution due to accelerations and deformations of the wire and mechanism.
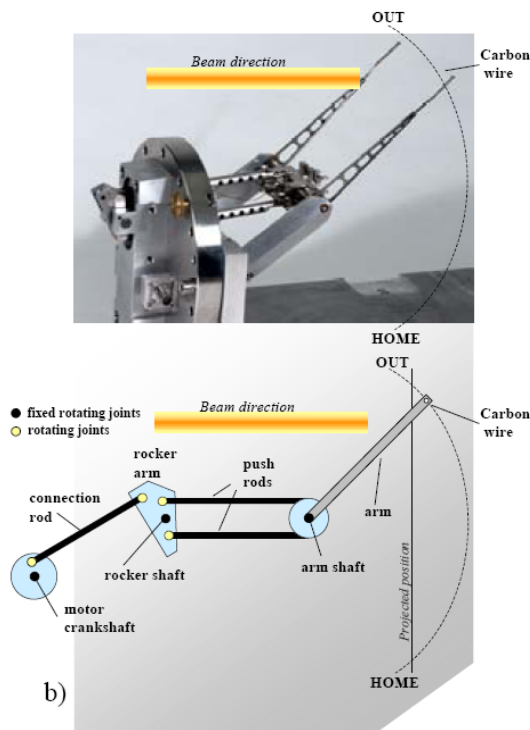

Figure 1: Picture (top) and schematics (bottom) of a rotative wire scanner used in the CERN low energy proton machines. The high current and fast acceleration ramp require fast scans. These devices can achieve 20m/s scanning speed.

Linear scanners are widely used in both linear and circular machines while rotative scanners are normally limited to circular machines.

The high speed may be necessary when a precise snapshot during the acceleration ramp is required or when the beam intensity is high and a slow scanner would get damaged.

In fact one of the most common problem with wire scanners is damage to the wire. Scanning high intensity or high density beams may lead to temperature increase on the wire above the limits and cause its rupture, Fig. 2 depicts a broken carbon filament at SLC. Typically wires are made of carbon fibres or tungsten, although quartz and beryllium wires are also used in special applications. The wire sizes range from a few microns to millimetres.

The resolution of this type of devices is mainly limited by the size of the wire, Eq. 1 shows the relation between the measured profile width, the real beam size and the wire radius. Although it is possible to deconvolute the three factors the final resolution can not be much better than the size of the wire.

$$\sigma_{meas} \cong \sqrt{\sigma^2_{beam} + r^2_{wire}} \qquad (1)$$

Among the best results, in terms of resolution, are those obtained at SLC (SLAC)[2][3] and ATF (KEK)[4] where resolutions of the order of few microns have been achieved. At SLC wire scanners were used extensively all over the machine (about 30 scanners) including the IP where the beam size was smaller than one micron.

Wire scanners are normally used as the reference instrument in the measurement of the transverse beam size and are installed in almost any machine.
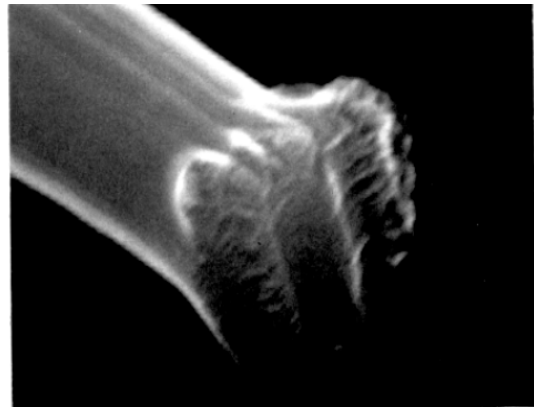

Figure 2: Broken 4μm carbon wire at SLC. It is possible to observe how successive pulses have eroded the wire.

SYNCHROTRON LIGHT

Another important technique for profile monitoring consists in imaging the synchrotron light emitted by the particles. Synchrotron light is radiated by charged particles when their trajectory is modified (curved), typically by a dipole magnet. In most cases the radiation emitted inside, or at the edge, of a lattice bending magnet is used, in this case the characteristics of the radiation are

imposed by the design of the accelerator lattice and may not be optimal for a profile monitor. Undulators or similar devices may be used to obtain a source with specific characteristics, better adapted for profile measurements; this is the case for example of the LHC synchrotron light profile monitors at CERN where dedicated super conducting undulators are used as synchrotron light sources at injection energy (450 GeV)[5].

The intensity of the synchrotron light as well as the spectrum depends heavily on the relativistic factor of the beam, the emission is therefore much more important for light particles like electrons and positrons.

$$\lambda_{cr} \propto \frac{R}{\gamma^3} \qquad P \propto \frac{\gamma^4}{R^2} \qquad (2)$$

Eq. 2 show the dependency of the critical wavelength λ_{cr} (emission drops sharply for wavelengths shorter than λ_{cr}) and of the total radiated power P from the relativistic factor γ and the bending radius R. The use of synchrotron light devices for proton machines is limited to high energy accelerators like the Tevatron at FNAL or LHC and SPS at CERN.

In general synchrotron light monitors consist of an in-vacuum "extraction" mirror, a view port, an optical telescope, a set of filters and a camera. Although the principle of these devices is rather simple, they can easily become complicated when the performances are pushed near the limits. In this case refractive optics may be replaced by spherical or parabolic mirrors in order to reduce the aberrations and the overall alignment requires a complicated system[6].

Synchrotron light monitors are passively observing radiation emitted by the beam, for this reason they can be used to continuously monitor the beam profiles during the acceleration or during a store offering a great potential for beam monitoring.

The ultimate resolution of synchrotron light imaging is given by diffraction and is closely dependent on the wavelength of the observed radiation. For this reason shorter wavelength allows better resolutions. At present several devices exists for observing synchrotron light in the x-ray range. The best results so far probably belong to the device developed at KEK-ATF where 3.23keV synchrotron light photons, selected using a monochromator, are focused by mean of a Fresnel Zone Plates microscope on an x-ray camera [7]. The resolution obtained is of the order of 2 microns.

LASER WIRE SCANNERS

In the wire scanners section it has been mentioned how the main limiting factors of these devices are the wire dimension (resolution) and the maximum beam density the wire can stand before being damaged. In order to overcome these limitations it is possible to replace the physical wire with a focused laser beam. In this case the minimum wire size is of the order of the laser wavelength, hundreds of nanometres, and there is no limit on the beam density. The detection is then quite different compared with a traditional wire scanner. The nuclear interactions between the beam and the wire and the secondary emission of surface electrons by the wire are not available. The main observable in case of LWS are inverse Compton scattered photons. In inverse Compton scattering a low energy photon (from the laser) interacts with the high energy particle (from the beam) and creates a high energy photon, usually in the x-ray or γ-ray range. The cross section for this process is however exploitable only for electrons and positrons. Another possible observable for LWS is the photo dissociation of H⁻ ions; in this case the laser photons are used to neutralize the H⁻ atoms producing hydrogen atoms and free electrons. The detection can be made by measuring the decrease in the beam current or by detecting the free, low energy, electrons.

Fig. 3 illustrates the schematics of a typical inverse Compton Laser Wire Scanner (LWS) system. The main components are: a high power pulsed laser, a complex system of mirrors and optics to steer and focus the beam, an interaction chamber, a bending magnet to separate the particle beam from the x-ray and the γ detector. In the inverse Compton process a consistent fraction of the energy of the electron is transferred to the photon, this means that the interaction produces degraded electrons on top of the x/γ-ray and these can also be detected, however the high energy photons provide usually a better signal.
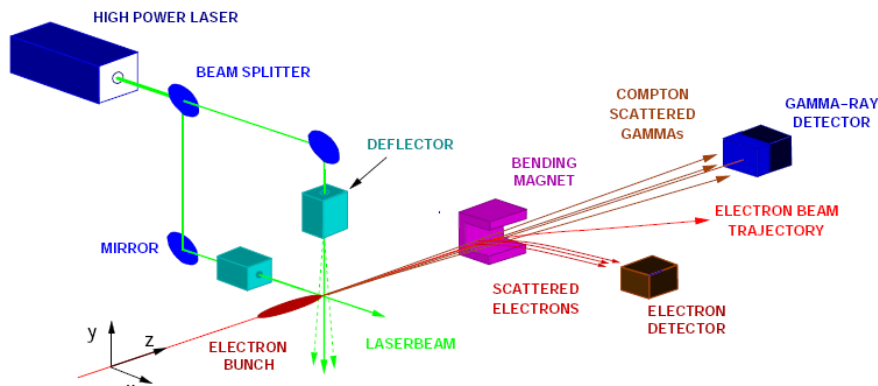

Figure 3: Schematics of a Laser Wire Scanner system

Laser wire scanners of this type have been used in many places: SLC[8], KEK-ATF[9], DESY-PETRA[10] etc. It is worth mentioning that at SLC profiles of about 1µm were measured at the IP. In this case the system was slightly different (see Fig. 4)[8], as the available space for the optics and the scanning mechanism was insufficient, the laser focusing was achieved using lenses and mirrors embedded in the interaction chamber and the electron and positron beams were scanned across the laser beam instead of the other way round.
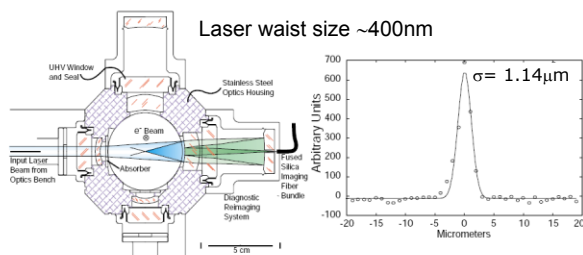

Figure 4: Schematics of the LWS installed on the SLC (left) and measured profile (right).

Another design of LWS was developed at KEK on the ATF damping ring [11]; instead of using a high power pulsed laser, a low power CW laser was used to feed a Fabry-Pérot optical cavity placed across the beam (Fig. 5). The cavity, composed of two high quality spherical mirrors, produces a focused laser beam at its centre with an enhancement of about a factor 1000 of the CW laser power. The waist size is 5.5µm and profiles down to about 7µm could be measured.
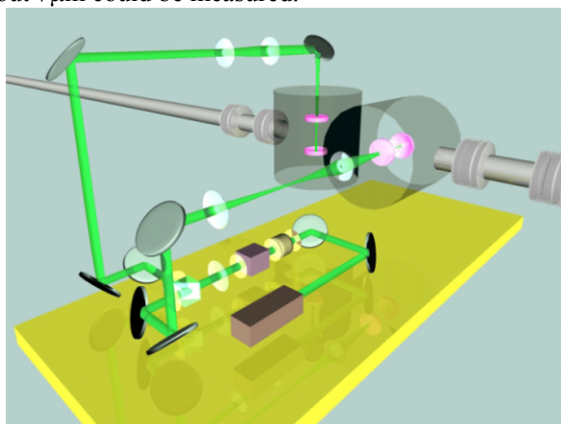

Figure 5: 3D schematics of the LWS system developed at KEK-ATF. The spherical mirrors of the optical cavities are depicted in pink. The green lines represent the laser beam.

A LWS for a H- beam has been developed and successfully used at SNS [12]. In the superconducting part of the SNS linac traditional wire scanners could not be used due to the risk of contaminating the SC cavities with broken wire filaments. A single laser beam is distributed along the linac with a complicated optics and switches system. Special electron detectors are placed at appropriate locations downstream of the laser wire stations and provide the detection signal.

One important advantage of LWS, on top of those already mentioned, is that it does not perturb the beam in a sensible way. This means that this type of devices can be used for continuous monitoring, something that traditional wire scanners can not do.

One limitation of LWS is that they can not be easily used to measure small flat beams. The length over which the laser can be focused, called Raleigh length, is in fact inversely proportional to the focused beam size. As was shown in Table 2 the electron and positron beams for future linear collider have aspect ratios of up to a factor 100 which will be difficult to measure with LWS systems.

OPTICAL TRANSITION RADIATION

Optical transition radiation (OTR) is emitted when a charged particle crosses the surface between two materials with different dielectric constant. The emission is similar to the bremsstrahlung effect and is due to the sudden annihilation of the image charge induced in the material. If a particle travelling in vacuum crosses a thin foil it will emit twice, once upon entering the foil (backward emission) and once upon exiting the foil (forward emission). In the backward emission the light is emitted in a direction as if the particle was reflected by the foil and converted into photons, the forward emission on the other hand is emitted in the same direction of the particle.

By tilting the foil it is thus very simple to direct the OTR outside of the vacuum chamber and there re-image it on a CCD camera obtaining a picture of the beam that impinged on the foil. Fig. 5 shows the sketch of a typical OTR system.
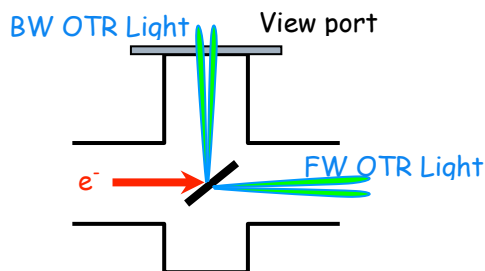

Figure 5: Schematics of the OTR emission mechanism.

In fact OTR based profile monitors are simply imaging systems like those used with scintillating screens. The main advantage of OTR over screens is the perfect linearity (no saturation or long decay times) and the high spatial resolution, basically only limited by diffraction. The spectrum of the BW OTR emission is very large and continuous, up to the plasma frequency of the foils material, covering the whole visible range. By using optical filters to select a narrow bandwidth in the blue or near UV the best resolutions can be achieved. The narrow bandwidth is necessary in order to reduce the effect of the unavoidable chromatic aberrations of the optical system.

OTR light is emitted with a peculiar angular distribution described by a sort of thick walled cone. The semi aperture of the cone is given by the relativistic factor

$1/\gamma$. This particular angular distribution means that special care has to be taken in the design of the optical system in order to assure that the vignetting effect does not perturb the measurement.

OTR devices are routinely used in both electron and proton machines anywhere the particles energy is sufficiently high (γ above 20 or so).

Another important aspect of OTR is that any foil, no matter how thin, will emit the same amount of light. This implies that very thin foils can be used inducing little perturbation on the beam itself. In the case of the LHC transfer lines for example 12μm Ti foils are used and several OTR stations can be acquired on the same beam pulse without any noticeable degradation of the beam parameters.

The use of thin foils also allows the observation of the evolution of the beam for several turns after injection in a circular machine. This type of observation is very important for the optimization of the matching of the optical functions of the transfer line and of the ring. Such measurements have been performed in the past in the SPS[13] at CERN and will be used in LHC.
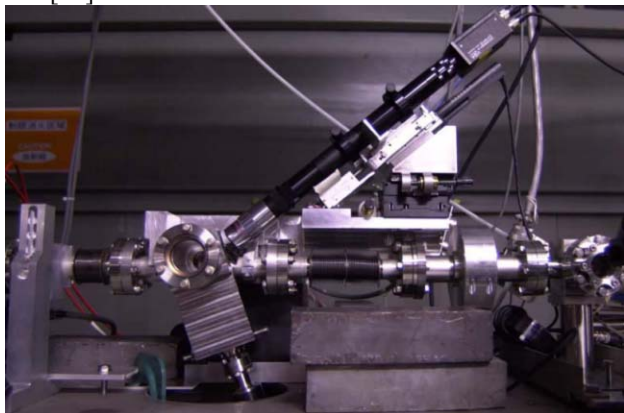

Figure 6: OTR station installed on the ATF extraction line at KEK. The electron beam arrives from the right and impinges on the radiator at an angle of ~10°. The OTR light is then analyzed by a far focus commercial microscope and a CCD camera; the black objects at an angle above the beam pipe.

The highest resolution so far using an OTR system has been achieved at KEK-ATF[14]. By using the system depicted in Fig. 6 beams of about 5μm were measured and the resolution was estimated to be around 2μm. The system is composed of a polished mirror (copper, beryllium and other materials have been tested) tilted 10° with respect to the normal to the beam. The OTR light, at ~20° to the beam, is focused using a commercial far focus microscope onto a CCD camera. During the experiments several radiators have been tested in order to understand the damage limits for the different materials. Fig. 7 Shows images of an electron beam taken on the ATF damping ring at KEK. The two sequences show how the radiator gets damaged in a few seconds when a focalized electron beam impinges upon. This constitutes one of the limitations of this type of detectors. Several materials

have been investigated; the results indicate that it will be difficult to develop a monitor for beams with particle densities above few 10^{15} e$^-$/cm^2.
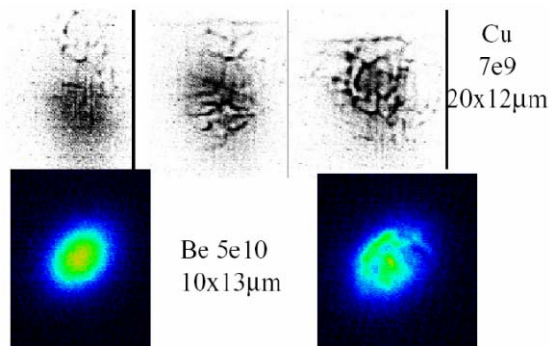

Figure 7: OTR images taken at KEK-ATF and illustrating the damage caused on the OTR radiator by the electron beam.

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