INSTRUMENTATION REQUIREMENTS FOR DIFFERENT ACCELERATOR TYPES

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Abstract

At present more than 15000 particle accelerators exist worldwide, being built and optimised to handle a large variety of particle beams for basic research and applications in industry and medicine. Diagnostic tools have been developed and optimised according to the special requirements of these machines and to meet the demands of their users. Storage rings for ultra cooled heavy ion beams, third generation synchrotrons for the production of high brilliant radiation, super conducting protons machines working at the energy frontier and finally linear electron accelerators for FEL applications or high energy physics are just the most prominent representatives of the large variety of accelerators. Each of them needs highly sophisticated tools to measure and optimise the corresponding beam parameters. Accordingly the issue addressed here is not to cover in full detail the different diagnostic devices but rather to concentrate on the aspects and needs as seen by the accelerator physicists and machine designers.

GENERAL CONTEMPLATIONS

The considerations presented here try to give a general overview about the needs in beam diagnostics for quite different machines. Clear enough there are beam parameter "standards" as orbits, beam intensity and lifetime that have to be measured, controlled and displayed in any machine. But given the large variety of accelerators optimised for different purposes there are also quite special needs and beyond the standards we will mostly outline the requirements of these beam parameters that need highly sophisticated measurements devices.

The spectrum of up to date accelerators covers a wide range: Proton or heavy ion storage rings running at the energy frontier as HERA, TEVATRON, RHIC and clear enough the LHC, and on the other side the low energy proton or heavy ion machines that are optimised for medical therapy. Then clear enough there are the special requirements of the electron machines that are optimised for synchrotron light production - be it as 3rd generation light sources or as FEL linacs. And in the end the planned high energy linear colliders that are not yet in their construction phase but already now set requirements for beam stability and control that have not been reached yet. These examples represent the extremes at least concerning the diagnostic tools that had to be established and we hope that talking about these, the large variety of accelerators that exist today like betatrons, cyclotrons, proton linacs are automatically included.

HIGH ENERGY PROTON MACHINES

The most prominent one today is clearly the Large Hadron Collider LHC [1] at CERN whose main parameters are listed in Table 1.

Figure 1: The LHC storage ring at CERN, Geneva.

Beam Parameters: The Standards

As in any (circular) accelerator the standard beam parameters that have to be measured are first of all the orbit and the tune in the two transverse planes. The requirements here differ not too much from other proton of heavy ion machines: beam sizes in the order of a millimetre or a certain fraction of it, and the usual golden rule to measure and control the orbit on the level of a tenth of the transverse beam dimension does not impose strong conditions on the beam position monitor system.

Table 1: LHC Main Parameters

LHC	
proton energy	7 TeV
particles per bunch	$1.2*10^{11}$
number of bunches	2808
beam current	0.582 A
stored beam energy	362 MJ
beam size (arc)	1.2mm ... 0.3 mm
bunch length	8 cm

Figure 2 shows one of the very first LHC beam orbits that were obtained during the beam commissioning in 2008. Before correction, the proton orbit in LHC in both planes was in the order of 5-10 mm, still to high for intense beams and clearly beyond the level that is required for high energy operation. After a few correction cycles however the required level of 1-2 mm rms had already been obtained.

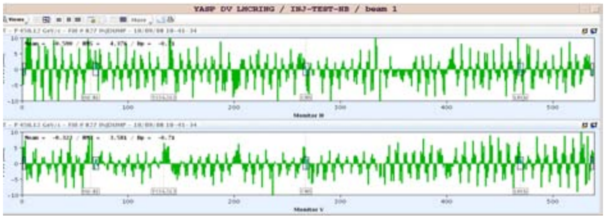


Figure 2: The very first beam steering in LHC.

An example for a tune signal in such a machine is shown in Fig. 3: It has been taken at the HERA collider [2] and shows the horizontal (left) and vertical (right) tune signal during luminosity operation: The tunes are set to their ideal values and - most important for these machines they are perfectly uncoupled.

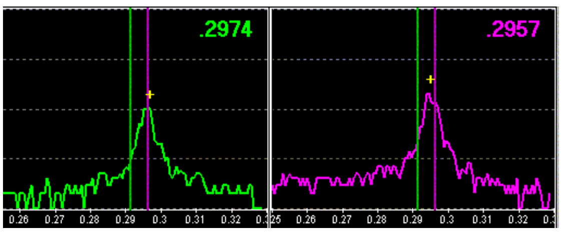


Figure 3: HERA tune measurement during luminosity operation.

More relevant than the bare measurement of the tunes in these high energy proton rings is the stability of the working point: The tunes have to be kept close to the design values during the complete machine cycles. Strong dynamic effects during the acceleration and decaying eddy currents during the injection and luminosity operation lead to intolerable drifts in the tune frequencies that have to be compensated [3]. A precise tune detection is needed that disentangles the two peaks even during operation close to the coupling resonance where these machines usually have to be operated. Unlike to electron machine however a strong beam excitation is excluded as it would destroy the beam quality. Therefore a very sensitive tune measurement is required combined with a sophisticated peak detection algorithm to control the tunes even at the coupling resonance. Figure 4 shows as an example the tune controller of the HERA proton ring: The trim quadrupoles used to control the working point are addressed bitwise allowing tune scans/control on a very precise manner and as demonstrated in the plot the diagnostics and control worked without problems even if the two tunes were interchanged during the operation [4].

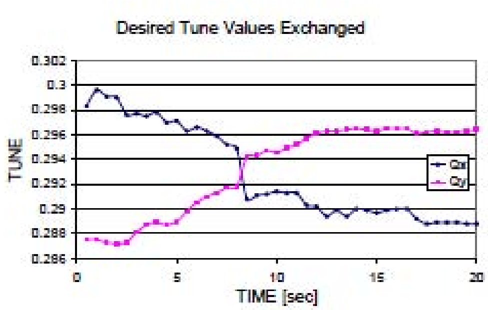


Figure 4: HERA tune controller: clear distinction of the working point even when crossing the tunes.

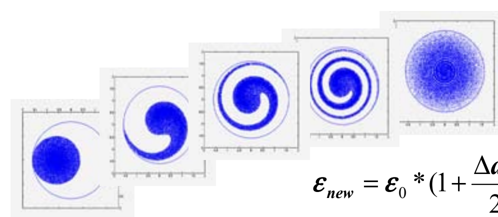
The Non-Standards

Beam quality in hadron machines is always a critical issue as scattering effects, instabilities and mismatch of orbit or optics during the beam transfer can easily lead to intolerable growth of the beam emittance and unlike to electron machines no damping effect due to synchrotron radiation can cure it. The emittance budget - especially during beam transfer - in these machines therefore is in general very tight: As an example we list in Table 2 the tolerances that are foreseen for the LHC pre-accelerator chain: Only small emittance growth is allowed and especially during the injection into the LHC the beam quality has to be guaranteed.

Table 2: Emittance Budget for the LHC Pre-accelerators

	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

To illustrate the problem, the effect of an offset Δa during beam injection is shown schematically in Fig. 5: Due to filamentation the original offset smears out in phase space and leads to emittance that is - as a rule of thumb - increased quadratically with the error [5].



$$\varepsilon_{new} = \varepsilon_0 * (1 + \frac{\Delta a^2}{2})$$

Figure 5: Schematical illustration of beam filamentation in phase space.

Similar effects exist for mismatched beam optics. To avoid these problems the beam position and angle as well as the optics mismatch have to be measured and eventually corrected. The well known keywords for the beam diagnostics in this context are (OTR)-screens, wire scanners and residual gas monitors.

In the case of LHC the beam energy is already high enough that even the synchrotron light emitted by the beam can be used as diagnostic tool [6]. The problem lies in the high energy and intensity of the stored beam. In LHC up to 2808 bunches are filled with 10^{11} protons each and carry an energy of up to 362 MJ. Diagnostics based on material interacting with the beam like wires or screens can not be applied anymore. Tests have been performed in the context of machine safety where a SPS beam of nominal energy (450 GeV) was dumped on a fixed target (Fig. 6).
Even at this relatively low energy severe damage occurs on any material that is hit directly by the beam.

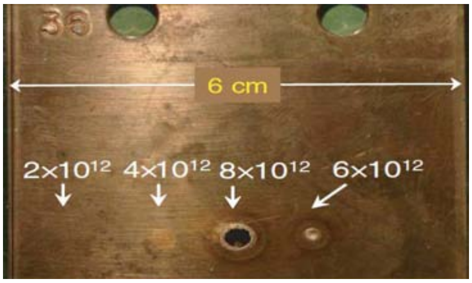


Figure 6: beam dump tests of a 450 GeV proton beam, being extracted from the SPS and dumped on a Cu target.

Wires or screens (Fig. 7) used so far in other machines, therefore are limited to very low beam intensities and the diagnostic tools foreseen in these cases are synchrotron light and residual gas monitors.

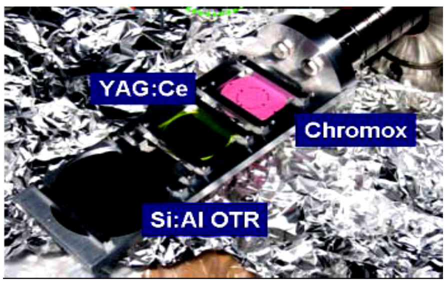


Figure 7: OTR and scintillating screens as diagnostic tools for low energy beams [7].

The strongest requirement for any high energy storage ring is related to the machine protection system: Given the LHC beam parameters any uncontrolled beam loss can easily lead to a quench of the super conducting magnets or even lead to severe damage of the storage ring components. Fig. 8 shows the result of an analysis that has been performed, studying magnet errors in the LHC and the resulting beam losses. In case of a severe magnet failure the damage level for machine components is reached already after 2 ms - corresponding to 25 turns in the machine.

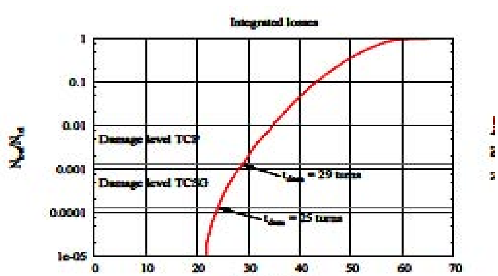


Figure 8: particle losses in LHC after a severe magnet failure: The damage level for machine components is reached already after 25 turns [8].

A very sensitive and at the same time fast beam loss monitoring system has to be established and completed by direct diagnostics of the hardware components [9]. At the same time fast beam current monitors are needed to detect beam losses on the level of $\Delta I/I = 10^{-6}$ on a turn by turn basis [10].

HADRON THERAPY MACHINES

Compared to the big super conducting storage rings discussed before, these machines are in a certain sense representing the other extreme. The typical beam energies of some MeV represent for the control and safety issues of the machine not really a problem. Typical beam parameters like several millimeter beam size and intensities of some 10^{10} particles per cycle neither set strong requirements for the beam diagnostics. The real challenge in this case lies in the control of the beam stability: Both concerning beam orbit and intensity the tolerances are tight and given by the medical application. These devices are driven typically by cyclotrons [11] or nowadays synchrotrons as e.g. in the case of the HIT project (Fig. 9) whose parameters are listed in Table 3:

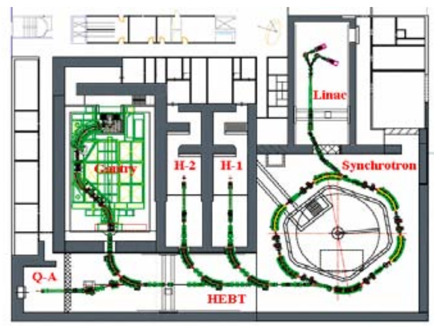


Figure 9: Layout of the Hadron Therapy Complex HIT

In the case of synchrotron based concepts the beam extraction in general is performed by a typical slow extraction scheme where the beam is put close to the third integer resonance (schematically shown in Fig. 10) and a smooth rf excitation is applied to increase the emittance in a controlled way and to obtain a constant extraction intensity.

Table 3: Typical Parameters of a Hadron Therapy Machine

HIT project	
particles	p, C, He, O
beam energy	50-430 MeV/u
beam size	4-10 mm
extraction time	1-10 s
extraction intensity	10 6 - 4*10 10 ions/spill
beam power	360 W dc

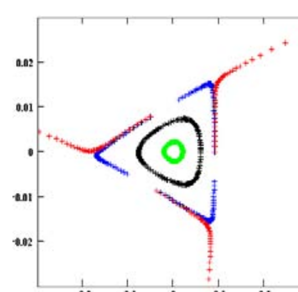


Figure 10: Schematical view in phase space of the slow extraction mechanism.

In the case of the HIT project the stored beam intensity of 10^{10} particles has to be extracted within a time span of typically ten seconds and the obtained intensity during this process should be constant on a level of 1 %. As a consequence the diagnostic elements have to measure beam currents in the order of fractions of nA in a non-destructive manner. The technique applied here in general is based on secondary emission monitors [12] and an example is shown in Fig. 11.

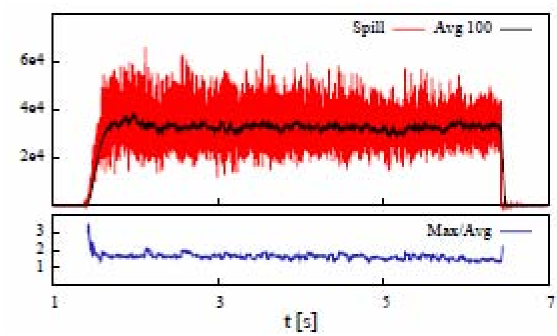


Figure 11: Measured particle flux during the slow extraction in HIT. The spill intensity corresponds to fractions of nA and has to be kept constant on a level of percent.

SYNCHROTRON LIGHT SOURCES

The modern 3rd generation synchrotron light sources represent for the case of electron accelerators again an extreme in beam quality and parameters and correspondingly in the requirements for the diagnostic tools. Here the standards like energy, tunes and beam intensity do not set severe restrictions to the diagnostic designers. The big challenge in this case is the measurement and control of the beam size and orbits. Both are closely related to the emittance and so of major importance for the brillance of the synchrotron light.

The brilliance of a synchrotron light source is given by

$$B = \frac{number\ of\ photons}{4\pi^2 \varepsilon_x \varepsilon_y * s * 0.1\% BW * A}$$

where BW indicates the bandwidth of the emitted light. Beside the beam intensity, the transverse emittances ε_x and ε_y are the main quality factor for these machines and usually these values are much smaller than those obtained in the high energy colliders as LEP or HERA-e. In Table 4 the beam energy and emittances are listed for a number of modern light sources. Values in the range of some nano meters are obtained.

Table 4: Energy and Emittance of Modern Light Sources

	ε_x (nmrad)	E (GeV)		ε_x (nmrad)	E (GeV)
PETRA 3	1	6	SLS	4.4	2.4
SPRING 8	3.4	8	ELETTRA	7	2.4
APS	3	7	BESSY 2	6	1.9
ESRF	3.9	6	SPEAR 3	18	3
DIAMOND	2.5	3	MAX 2	9	1.5
SOLEIL	3	2.5	ANKA	90	2.5

Again the golden rule for orbit stability and control is a required BPM resolution in the order of 10 % of the beam size. Referring now e.g. to the PETRA 3 light source [13] which is in the commissioning phase at present, we have to deal with beam sizes in the order of micro meters. 220 electrostatic beam position monitors (BPMs) are forseen in this storage ring that are supposed to measure the closed orbit with a resolution of 0.3 µm (rms). Beside this high quality BPMs the synchrotron light itself is clearly used as diagnostic tool in these machines. However again the requirements are extreme and the beam parameters demand state of the art techniques.

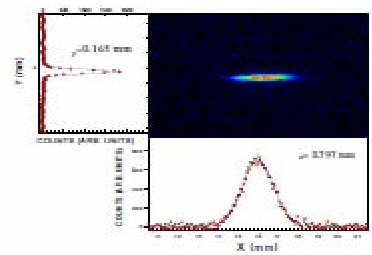


Figure 12: Synchrotron light image of the electron beam in the APS accumulator ring.

Applying Heisenberg's uncertainty principle to the synchrotron light diagnostics [14] we obtain an equation that relates the resolution for position measurements to the opening angle $\Delta\psi = 1/\gamma$ of the light cone:

$$\Delta\sigma = \lambda * 2\Delta\psi$$

Assuming e.g. an electron beam of 1 GeV and a wavelength of the emitted light of λ = 500nm we obtain for the uncertainty of the position measurement $\Delta\sigma$ = 500 µm, by far not small enough to meet the requirements. Any position measurement in modern light sources therefore is principally limited by this diffraction effect. To overcome this problem interferometric techniques are applied and pinhole cameras [15].

SASE FELS

Referring to the measurement of "standard parameters" that we already discussed in the previous examples, for the FEL machines we are allowed to state that there are no standards. The beam parameters are pushed to new limits and completely new techniques are needed to diagnose them. As an example the European X-FEL project [16] under construction at present at the DESY institute is sketched in Fig. 13: The 3.4 km long device consists of several linear accelerator parts, 2 bunch compressors and finally a 250m long undulator section where the SASE process takes place.

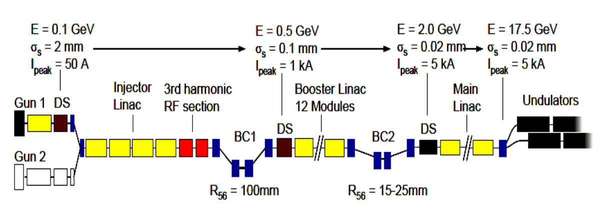


Figure 13: The European X_FEL project at DESY.

The parameters of this machine are listed below (Table 5); the special requirements marked in red. Again, according to the special parameters of the particle beam in these machines and the characteristics of the emitted light, dedicated measurement devices have to be developed: The SASE process is principally of statistical nature and so the properties of the single bunches have to be measured. Therefore any diagnostic tool has to be non destructive, based on single pass -single bunch signals and very fast to provide input for the control system within a bunch train.

Table 5: Parameters of the European X-FEL Project

Euro X-FEL	
light wave length	1Å
beam energy	20 GeV
normalised emittance	1.4 mm mrad
undulator length	250 m
beam pulse length	650 μs
number of bunches	3250
bunch spacing	250 ns
bunch length	70 fs
brilliance (photons/0.1%BWmm^2mrad^2s)	$5*10^{33}$
absolute emittance	$4*10^{-11}$ m*rad

Especially the orbit stability within the undulator is of crucial importance as here the electron beam has to overlap with the light fan produced. A stability of the orbit in the order of 3 µm for the rms orbit is required inside the complete undulator length of 250 m. To achieve these constraints a so-called intra bunch feedback system is required that can measure the orbit of a single bunch within a conversion time of 200 ns, analyse the measurement and apply correction settings for the upstream bunches within the bunch train. Those requirements cannot be fulfilled by standard button pick up monitors. To achieve the high precision/ resolution and even more the fast response time required by the Intra Bunch Train Feedback System, new techniques had to be developed and the keywords here are resonant strip line BPMs and re-entrant cavity monitors. Beside the measurements of the beam orbit, the emittance of the bunches are of major importance for the SASE process. Being defined - much like in a proton machine - by the properties of the particle source the beam emittance has to be kept constant over the complete beam transport system and acceleration procedure. Even more it is the so-called slice emittance that determines the SASE process: During its path along the undulator the bunch interacts with the emitted light and micro bunches (slices) are formed that define the coherent emission. The measurement of these slice emittances requires time resolutions of smaller than pico seconds. In general it is based on transverse deflecting RF structures that shear the bunch e.g. into the vertical plane to project the horizontal versus longitudinal bunch profile onto a screen and a streak camera. Using this technique a time resolution of sub-pico seconds is achieved and the emittance of the micro bunches can be obtained. An example of such a measurement, obtained at FLASH is shown in Fig. 14. The length of the slices in this case corresponds to 30 femto seconds.

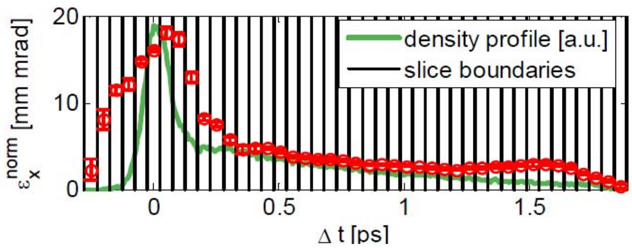


Figure 14: Slice emittance measurement at FLASH.

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