INTRODUCTION TO BEAM INSTRUMENTATION AND DIAGNOSTICS

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Abstract
These lectures aim at describing instruments and methods used for measuring beam parameters in circular accelerators. Emphasis will be given to new detection and analysis techniques in each field of accelerator instrumentation. The clear distinction is made between “instrumentation”, i.e. the design and construction of the instruments themselves and “diagnostics”, the use of the data from these instruments for running and improving the performance of the accelerator.

INTRODUCTION
Beam instrumentation and diagnostics combines the disciplines of accelerator physics with mechanical, electronic and software engineering, making it an extremely interesting field in which to work. The aim of the beam instrumentation physicist or engineer is to design, build, maintain and improve the diagnostic equipment for the observation of particle beams with the precision required to tune, operate and improve the accelerators and their associated transfer lines.

This introduction is intended to give an overview of the instrumentation in use in modern synchrotrons. The choice available today is so vast that inevitably it will not be possible to cover them all. Many of the standard instruments have been covered in previous CAS schools (see for example Ref. [1] which also contains a comprehensive list of references) and will therefore be touched upon only briefly, with more emphasis being given to new and innovative measurement techniques and their use in beam diagnostics. The following subjects will be discussed:

1. Beam position measurement
2. Beam current measurement
3. Diagnostics of transverse beam motion (tune, chromaticity and coupling)
4. Emittance measurement
5. Beam loss monitoring
6. Luminosity measurement
7. Some examples of beam diagnostics

1. BEAM POSITION MEASUREMENT
The Beam Position Monitor (BPM) can be found in every accelerator. Its role is to provide information on the position of the beam in the vacuum chamber at the monitor location. For linacs and transfer lines the BPMs are used to measure and correct beam trajectories, while for synchrotrons such monitors are distributed around the ring and used to calculate the closed orbit. In circular machines, their location is usually chosen close to the main quadrupole magnets where the $\beta$-functions are largest and so any orbit distortion a maximum. For 90° lattices a typical layout involves placing horizontal monitors near the focusing quadrupoles (where the horizontal $\beta$-function is large) and the vertical monitors near the defocusing quadrupoles (where the vertical $\beta$-function is large). Apart from closed orbit measurements, the BPMs are also used for trajectory measurements (the first turn trajectory is particularly important for closing the orbit on itself) and for accelerator physics experiments, where turn-by-turn data, and even bunch-to-bunch data is often required.
In the early days a BPM monitoring system simply consisted of an oscilloscope linked directly to the pick-up signals. Since then, enormous advances in the acquisition and processing electronics have been made, turning beam position monitors into very complex systems. Modern BPMs are capable of digitising individual bunches separated by a few nanoseconds, with a spatial resolution in the micron range, while the resulting orbit or trajectory collected from several hundred pick-ups can be displayed in a fraction of a second.

1.1 Pick-ups

The measurement of beam position relies on processing the information from pick-up electrodes located in the beam pipe. Five pick-up families are commonly employed:

- Electrostatic – including so-called ‘button’ and ‘shoe-box’ pick-ups
- Electromagnetic – stripline couplers
- Resonant cavity – especially suited for high frequency linacs
- Resistive
- Magnetic

An excellent in depth analysis of most of these pick-ups is presented in Ref. [2]. Here we will briefly describe the two most commonly used, namely the electrostatic and electromagnetic pick-up.

1.1.2 Electrostatic (Capacitive)

The electrostatic or capacitive pick-up is the most widely used in circular accelerators. It consists of metallic electrodes situated on opposite sides of the vacuum chamber at the location where the beam is to be measured. As the beam passes through, electric charges are induced on the electrodes, with more induced on the side which is closer to the beam than the one furthest from the beam. By measuring the difference in the charge induced, the position can be calculated. Let us analyse the properties of button pick-ups (see Fig. 1) since they are the most popular due to their cheapness and ease of construction.

![Fig. 1 Cross-section and photo of an LHC button electrode.](image-url)

The image current associated with the beam will induce charges on the button which are proportional to the beam intensity and inversely proportional to the position of the beam from the electrode. A schematic representation is given in Fig. 2.

The figure of merit for any electrode is its transfer impedance (the ratio of the pick-up output voltage, $V$, to the beam current, $I_b$). For a capacitive pick-up the signal is proportional to the rate of change of beam current at low frequencies, while for high frequencies the capacitance ‘integrates’ the signal and the transfer impedance tends to its maximum. For the case of a button electrode of area $A$ and capacitance $C$ situated at a distance $d$ from the beam the maximum transfer impedance (i.e. the
value it tends to at high frequency) can be approximated by:

$$Z_{Fe} = \frac{A}{2\pi d(\beta c) C}$$

Button electrode capacitances are typically in the 10pF range. Impedance transformation can be used to improve the low frequency response at the expense of that at high frequency. Figure 3(a) shows the frequency response of an 8pF button electrode for the matched 50Ω impedance case (1:1) and after two different impedance transformations. The time response of the button for different bunch lengths can be seen in Fig. 3(b).

![Fig. 3 Schematic of a capacitively coupled electrode.](image)

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![Fig. 3 Frequency (a) and time (b) response of a button electrode.](image)

(a)  
(b)

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When designing such pick-ups care must be taken to limit the impedance variations when the transmission line used for signal extraction passes from the vacuum to a feedthrough or cable dielectric (such as ceramic, glass or air). Any such mismatch will produce unwanted reflections, often at high frequency, which could perturb the processing electronics. For this reason most processing chains introduce a low-pass filter on the button output. Special care must also be taken to pair the electrodes on opposite sides of the chamber to minimise offsets in the position reading. This pairing can be made less sensitive to capacitance variations if the high frequency cut-off for the processing electronics sits on the linear part of the button response, with the disadvantage that the overall signal amplitude is reduced.
1.1.3 Electromagnetic (stripline)

The electromagnetic pick-up is a transmission line (stripline) which couples to the transverse electromagnetic (TEM) field of the beam. The transmission line is formed between the stripline and the wall of the vacuum chamber and is excited by the beam only at the gaps on either end of the stripline where a longitudinal field occurs. Fig. 4 shows the layout of such an electromagnetic stripline electrode.

Consider a bunch travelling from left to right (upstream to downstream). While it is over the upstream port there is a voltage $V_r$ across $R_U$, causing a voltage wave of that amplitude to be launched to the right. The stripline forms a transmission line with the wall of the vacuum chamber of characteristic impedance $Z_0$. The voltage wave is therefore accompanied by a right travelling current wave of amplitude $I_r = V_r / Z_0$. This current flows along the bottom surface of the electrode whilst an equal and opposite current flows along the chamber wall. In addition an image current of amplitude $\eta I_B$ travels along the top surface of the electrode. The voltage $V_r$ across $R_U$ can therefore be expressed as

$$V_r = (-I_r + \eta I_B)R_U = \eta I_B \frac{R_U}{R_U + Z_0} \Rightarrow V_r = \frac{1}{2} \eta I_B Z_0$$

for a matched stripline ($R_U = Z_0$).

When the beam is over the downstream port it produces a voltage $-V_r = -\frac{1}{2} \eta I_B Z_0$ across $R_D$ in the same way as it produced a voltage $+V_r$ across $R_U$. This launches a left-travelling wave of the same magnitude, but different sign to the right-travelling wave, which propagates along the transmission line formed by the stripline and the chamber wall and will produce an inverted signal upon arrival at the upstream port a time $L/c$ later. The final signal observed at the upstream port will therefore be a bipolar pulse with the maxima separated by $2L/c$ (see Fig. 5(a)).

When the RF wavelength of the beam is equal to multiples of $2L$, the reflection and the signal from next bunch will cancel and there will be no net signal from the stripline. A maximum in the frequency response will be observed when $L$ is a quarter of an RF period, and hence the stripline pick-up...
up length is usually chosen accordingly. The full frequency response of a 60cm long stripline is shown in Fig. 5(b) and has a lobe structure, with the minima located at multiples of \(c/(2L)\).

For a relativistic beam the voltage due to the beam passing the downstream port is produced at the same time as the right-travelling wave propagating between the stripline and the wall arrives at the downstream port. The two equal and opposite voltages therefore cancel producing no net signal at the downstream port. The electromagnetic stripline pick-up is therefore said to be “directional”, i.e. a signal is only observed on the upstream port with respect to the beam direction. These pick-ups are therefore used in all locations where there are two counter rotating beams in the same vacuum chamber. Due to the imperfections in the stripline and feedthrough impedance matching, the best directivity one can hope to obtain for a real stripline is generally around 25-30dB (i.e. the voltage signal of one beam with respect to the other is attenuated by a factor between 18-32).

### 1.2 Beam Position Acquisition Systems

Once the signals from the opposite electrodes of a pick-up have been obtained, the next step is to convert these signals into a meaningful beam position. The first thing to do is to normalise the position, i.e. to make it independent of the signal amplitude (or beam intensity). This is generally done using one of three algorithms, whose response curves can be seen in Fig. 6.
- **Difference over sum (Δ/Σ)** - The sum and difference can be obtained either using a 0°/180° passive hybrid, a differential amplifier or calculated by software (after digitising), to give:

\[
\text{Normalised Position} = \frac{A - B}{A + B}
\]

The transfer function of this algorithm can be seen to be highly linear.

- **Logarithmic ratio** - The two input signals are converted into their logarithmic counterparts and subtracted. In practice this is done using logarithmic amplifiers followed by a differential amplifier. This gives:

\[
\text{Normalised Position} = \log(A) - \log(B) = \log\left(\frac{A}{B}\right)
\]

whose response curve is seen to be an reversed S-shape, which becomes highly non-linear when exceeding 70% of the normalised aperture.

- **Amplitude to Phase** - The two input signals are converted by a 90° passive hybrid into signals of equal amplitude but varying phase, with the position dependence of this phase given by:

\[
\text{Normalised Position} = \phi = 2 \times \text{ArcTan}(A/B)
\]

Here the transfer function again deviates from the linear in an S form, but does not diverge for large excursions. In addition, the gradient is larger around zero, making it more sensitive towards the middle of the pick-up. A variation on the amplitude to phase algorithm is amplitude to time conversion, which will be discussed in more detail below.

The type of algorithm to be used will depend on the choice of processing electronics. In all cases the non-linearity is taken into account by calibration circuits and correction algorithms. A summary of commonly used beam position acquisition systems is given in Fig. 7.

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Fig. 7 Schematic representation of the various beam position processing families.  
( courtesy of G. Vismara, CERN )
Here we will only briefly mention the various families in passing, but detailed descriptions along with the advantages and disadvantages of each system can be found in ref [3].

MPX (multiplexed) – each of the BPM electrodes is multiplexed in turn onto the same, single acquisition electronics chain. This eliminates channel to channel variations, but since the switching is generally quite slow such an acquisition tends to be used in circulating machines where only the average orbit is of importance.

Hybrid (Sigma & Delta) – here a $0^\circ/180^\circ$ passive hybrid is usually used to give the sum ($\Sigma$) and difference ($\Delta$) signal from the two electrodes. The position (or ratio of the sum and difference signals) can then be obtained in many ways including: direct digitisation, homodyne detection (mixing the sum and delta signals with the sum signal itself) or heterodyne detection (mixing sum and delta signals with an external reference).

Individual Treatment – in this case each electrode is treated separately, but in parallel. The acquisition can either consist of directly digitising each signal or using logarithmic amplifiers as outlined above. The disadvantage of this method is that it requires two (or four depending on the pick-up orientation) very well matched chains of electronics, since the combination of the signals to obtain a position is performed at the very end of the chain.

Passive Normalisation – here the amplitude difference (i.e. position information) in the input signals is directly converted into a phase or time. Intensity information is lost in this procedure, but the result is a varying phase or time which is directly proportional to the position.

1.2.1 Wide-Band Time Normalisation

The LHC beam position system will be based on a new concept of amplitude to time normalisation, so-called “wide-band time normalisation” or WBTN (see ref [4]). This was developed with two main aims in sight; to provide bunch by bunch beam position information (requiring one measurement every 25ns for the LHC) and to avoid the necessity of gain switching (requiring that one chain of electronics cope with a factor 40 difference in single bunch intensity). The principle of the WBTN technique is outlined in Fig. 8.

![Fig. 8 The wide band time normalisation principle.](image)

The signal from a single pick-up electrode is split and recombined with a delayed signal from the other electrode. This results in two signals where the relative zero crossing time depends on the position of the beam. In the case of the LHC the position information is converted into two pulses separated by $10 \pm 1.5$ns (the position being encoded into the $\pm1.5$ns). To obtain the required resolution and linearity using such a system requires precision high frequency electronic engineering. For example in order to achieve the 0.1% single shot resolution requested for the LHC (50µm on a 50mm diameter pick-up) a stability and reproducibility at the 3ps level is required. One advantage of this system is that once the position has been encoded into these two pulses, it can be transmitted in a digital manner over a fibre optic network. This is important for machines such as the LHC where the
amount of electronics in the tunnel, in particular digital electronics, has to be minimised due to radiation levels. Fibre-optic transmission allows all the digital processing electronics, which finally extract the position from the time difference, to be regrouped in surface buildings, where they are accessible and free from radiation concerns. The final implementation layout for the LHC WBTN system is shown in Fig 9.

2. BEAM CURRENT AND INTENSITY MEASUREMENT

The measurement of beam current or bunch intensity is one of the most basic measurements performed at any accelerator. This is usually done by means of a “beam current transformer” or BCT. In order for the transformer to interact with the magnetic field of the beam it has to be placed over a ceramic gap in the vacuum chamber. To keep the impedance seen by the beam as low as possible an RF bypass (either a thin metallic coating or external capacitors on the ceramic) is required for the high frequency wall current components. In addition, to keep the vacuum chamber continuity, an Ohmic bypass external to the transformer is needed.
2.1 The Beam Current Transformer

The beam current, $I_B$, can be considered as the primary winding of the transformer, with the output voltage from the secondary windings given by $V = L \frac{dI_B}{dt}$. An ideal transformer would give a differentiated response, with the integrated charge being zero, which is not of much use as a measuring device. In reality the secondary windings have some stray capacitance, and are terminated by some finite resistance. This leads to signals of the form shown in Fig. 10. The transformer output now closely resembles the beam intensity distribution, with the added inconvenience of a DC offset due to the transformer droop. This DC offset can be corrected for either electronically or, in this modern era, by software treatment of directly digitised data.

A transformer with a bandwidth from 200Hz to 1GHz has recently been installed in the CERN-SPS [5]. Such a bandwidth is obtained by using a ferromagnetic core wound of high permeability metal tape to avoid eddy currents. With this instrument, operators can observe the bunch-by-bunch intensity evolution of beams destined for the LHC throughout the SPS acceleration cycle. In order to obtain the total charge in each bunch, fast integrators are required which are capable of working at repetition frequencies of up to 40MHz. Such an integrator chip has been developed by the Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France, for capturing photomultiplier signals in the LHC-b experiment [6], and is now also used for bunch intensity measurements. A schematic of the integration principle and the resulting signals as measured in the CERN-SPS are shown in Fig. 11. The chip works using two integrators in parallel. As one integrates the other is discharged, with the output switched from one to the other on each clock cycle. The resulting integrated amplitude (voltage) is directly digitised, with all gain linearisation and DC offset subtraction performed by software.

![Fig. 11 The principle and measurement of the CERN-SPS fast beam current transformer.](image)

2.2 The DC Beam Current Transformer

In storage rings and accelerators with cycle times of several seconds, a DC beam transformer can be used to measure the total current. Such an instrument was developed for the CERN-ISR (Intersecting Storage Rings), the first machine to sustain beams for hours [7]. A DC transformer is based on a pair of matched, toroidal, ferromagnetic cores, which are driven into saturation by a modulation current at frequencies of up to a few kHz. The principle of operation is shown in Fig. 12, and makes use of the hysteresis loop of the toroid. If an equal but opposite modulation current (the triangular waveforms in Fig. 12) is applied to both cores with the beam not present, then the voltage induced in the detection windings on each core will also be equal but opposite. When, however, there is a beam current $I_B$ present, the starting point in the hysteresis loop for zero modulation current is offset due to the static magnetic field generated by the beam current. Since the modulation is opposite in each toroid, the time spent in saturation will be different for the two branches of the hysteresis loop. This results in the...
generation of voltage pulses at twice the modulation frequency when the induced voltage in the detection windings on each core is combined. The demodulation of this signal gives a train of pulses, with the width of each pulse being a direct measure of the beam current, i.e. by how much the hysteresis curves are offset.

In the “zero flux detector” implementation of the DC beam transformer, the result of the demodulation is fed back into a compensating current loop (see Fig. 12). Once the compensation current and the beam current are identical the net static magnetic field seen by the toroids is zero (hence zero flux) and the output from the demodulator is also zero. The beam current can then be obtained by simply measuring the voltage produced by this compensation current across a known resistor.

For modern DC transformers such a zero flux detector is used to compensate the droop of the simple beam current transformer described in section 6.2. This significantly increases the bandwidth of the system, allowing measurement from DC to a few MHz.

3. DIAGNOSTICS OF TRANSVERSE BEAM MOTION

The instrumentation used to look at transverse beam motion is very important to the efficient operation of any circular accelerator [8]. There are three main parameters which can be measured using such diagnostics, namely the betatron tune, chromaticity and coupling, all of which are discussed in detail below.
3.1 Tune Measurement

All betatron tune measurements are based on applying a transverse excitation to the beam and looking at the resulting beam response. The most common methods of performing such measurements are presented in this section.

3.1.1 Fourier Transform (FFT) of beam motion

In the simplest case the beam is given a single kick using a powerful stripline or magnetic kicker, and allowed to oscillate freely (alternatively white noise can be injected onto the beam). The observation of the resulting beam motion is usually carried out using one of the types of position pick-ups covered in Section 1. Once the data has been recorded, the power density spectrum in frequency domain can be computed using a Fast Fourier Transform (FFT). The betatron tune is determined as the frequency which has the highest amplitude response. If there is enough external excitation from other sources (ground motion, power supply ripple etc) or the beam is slightly unstable by itself, the method also gives useful information without any specific beam excitation.

What is usually of most interest for particle colliders is to be able to track the tune evolution during the whole of the accelerator cycle. The simplest way of achieving this is to repeat the tune measurement outlined above at regular intervals. By displaying such data as a spectrograph (Fig. 13(a)) the complete history of the tune during the machine cycle can be tracked.

3.1.2 Chirp Excitation

In order to minimise the frequency range over which power is put into the beam, swept frequency or “chirp excitation” is often used (so-called because if listened to at audio frequencies such a signal sounds like the chirp of a bird). The chirp range is set around the expected betatron tunes and the sweep time is determined depending on the requested time resolution and precision of the tune measurement. The advantage of this technique is that in addition to an amplitude response it also gives phase information, as the phase difference between the observed motion and the applied sine wave is easily measured. This makes it more sensitive than the single kick method and so allows smaller excitation amplitudes to be used. Fig. 13(b) shows a result from the CERN-SPS where a chirp was...
performed every 30ms. The sine wave can be seen to sweep from low to high frequency, with the main tune peak and the synchrotron satellites clearly visible.

3.1.3 Swept Frequency Analysis
For this method (often called “Network Analysis”) the beams are excited with a steady sinusoidal wave. The amplitude and phase of the resulting oscillation are precisely determined by means of harmonic analysis. Thereafter the excitation frequency is increased in steps until the range of interest is covered. This represents a very precise measurement yielding the full information of the beam transfer function. The disadvantage is the long measurement time, which renders the method of little use for the study of dynamic phenomena.

![Complete beam transfer function measured using swept frequency analysis in the CERN-LEP.](image)

Fig. 14 Complete beam transfer function measured using swept frequency analysis in the CERN-LEP.

Such a complete beam transfer function is shown in Fig. 14. Notice how the phase jumps by 180° as the excitation sweeps across the betatron tune frequency. Such a response is typical of any harmonic oscillator. Since the rate of change of the phase change is a maximum at the peak of the amplitude response, measurements performed using the phase response of the beam are in general more sensitive that those relying on amplitude response.

3.1.4 Phase Locked Loop Tune Tracking
In order to have a fully continuous measurement of the tune a Phase Locked Loop (PLL) needs to be implemented. The basic principle of the PLL is sketched in Fig. 15. A voltage or numerically controlled oscillator (VCO or NCO) is used to put a sine wave excitation, $A \cdot \sin(\omega t)$, on the beam. The beam response to this signal is then observed using a pick-up, and will be of the form $B \cdot \sin(\omega t + \phi)$, where $\phi$ is the phase difference between the excitation and the observed signal. In the phase detector the excitation signal and the observed signal are multiplied together, resulting in a signal of the form $A \cdot B \cdot \sin(2\omega t + \phi) \cdot \cos(\phi)$, which is seen to have a DC component proportional to the cosine of the phase difference. This will therefore be zero when the phase difference is 90° which, as was seen above, is where the amplitude response is a maximum, i.e. at the tune frequency. The aim of the PLL is to “lock-in” to this 90° phase difference between excitation and observed signal by correcting the VCO frequency until the DC component of the phase detector output is zero. Since the PLL will always try to maintain this 90° phase difference, the VCO frequency will track any tune changes, so giving a continuous tune measurement.

In practice things are not quite as simple. Many parameters have to be optimised in order to for the PLL to find, lock-in and subsequently track the tune peak. The beam spectra and dynamics also have to be well understood if the PLL is not to lock or jump to a spurious line, resonance, synchrotron sideband etc. In addition, for hadron machines, the continuous excitation will lead to emittance blow-up. In order for this to be kept to a minimum the applied excitation has to be small and therefore the
observation pick-up and following electronics very sensitive. This is less of a problem for lepton colliders where radiation damping takes care of any emittance blow-up caused by the excitation, making PLL systems much easier to implement on such machines.

3.2 Chromaticity Measurement

For any high energy synchrotron, the control of chromaticity is very important. If the chromaticity is of the wrong sign (corresponding to positive below the transition energy or negative above it) then the beam quickly becomes unstable due to the head-tail instability. If the chromaticity is too big then the tune spread becomes large and some particles are inevitably lost as they hit resonance lines in tune space. The most common method of measuring the chromaticity of a circular machine is to measure the betatron tune as a function of the beam energy and then to calculate the chromaticity from the resulting gradient. This is usually done by varying the RF frequency, keeping the magnetic field static. The equations of interest are:

\[
\Delta Q = \left(\xi Q\right) \frac{\Delta p}{p} = Q' \frac{\Delta p}{p} = Q' \frac{R}{R} \frac{\Delta R}{R} = Q' \frac{\Delta f}{f} \left(\frac{-\gamma_i^2 \gamma_i^2}{\gamma_i^2 - \gamma_i^2}\right) = \frac{\Delta f}{f}
\]  

(3.1)

where \(\Delta Q\) is the change in tune, \(\Delta p/p\) the momentum spread (or relative change in momentum), \(\Delta R/R\) the relative change in radius, \(\Delta f/f\) the relative change in RF frequency and \(\xi\) the chromaticity. Please note that the chromaticity, \(\xi\), is often expressed as \(Q' = Q \xi\), where \(Q\) is the total betatron tune including the integer part.

In the CERN-SPS, for example, a chromaticity measurement consists of performing a tune measurement for three different RF frequency settings. Instead of noting the exact RF frequency, what is actually measured is the change in closed orbit, from which the relative change in radius can be calculated. These three points are then plotted, with the gradient giving the chromaticity.

In order to obtain continuous chromaticity measurements this technique of RF modulation is combined with the PLL tune measurement outlined in the previous section. The RF frequency is usually programmed with a small asymmetric function which periodically varies about the mean RF frequency. By tracking the tune during this time using the PLL and knowing the magnitude of the RF change, the chromaticity can be calculated and tracked. An example of such a measurement performed at the CERN-LEP is shown in Fig. 16.

Fig. 15 Principle of a phase locked loop tune tracker.

\[
\text{Frequency Control}
\]
3.2.1 Head-Tail Chromaticity Measurement

The methods outlined above do not allow instantaneous chromaticity measurements, for instance during energy ramping or beta squeezing and are limited to repetition intervals in the Hz range. In preparation for the LHC a new approach has been developed which uses the energy spread in the beams for a chromaticity measurement. Transverse oscillations are excited with a single kick and the chromaticity is calculated from the phase difference of the individually sampled head and tail motions of a single bunch. Using this method the chromaticity can be calculated using the data from only one synchrotron period (about 15-50 milliseconds in the case of the LHC). In addition, this technique does not rely on an accurate knowledge of the fractional part of the betatron tune and, for a machine operating well above transition, the calculated chromaticity is virtually independent of beam energy.

Assuming longitudinal stability, a single particle will rotate in longitudinal phase-space at a frequency equal to the synchrotron frequency. During this longitudinal motion the particle also undergoes transverse motion. If the chromaticity is zero, then the particle will have the same tune wherever it is in the bucket. As soon as chromaticity is non-zero, however, the particle’s tune will change depending on where it happens to be longitudinally. If a whole bunch of particles is kicked transversely, then the resulting transverse oscillations for a given longitudinal position within the bunch can be shown [9] to be given by

\[ y(n) = A \cos\left(2\pi n Q_0 + \omega_z \tau \left(\cos(2\pi n Q_s) - 1\right)\right) \]  (3.2)

where \( n \) is the number of turns since the kick, \( Q_0 \) is the betatron tune, \( Q_s \) is the synchrotron tune, \( \tau \) is the longitudinal position with respect to the centre of the bunch and \( \omega_z \) is the so-called chromatic frequency given by

\[ \omega_z = Q' \frac{\omega_0}{\eta} \]  (3.3)

Here \( Q' \) is the chromaticity, \( \omega_0 \) is the revolution frequency and \( \eta = 1/\gamma^2 - 1/\gamma_p^2 \). If we now consider the evolution of two longitudinal positions within a single bunch separated in time by \( \Delta \tau \), then from (3.1) it follows that the phase difference in the transverse oscillation of these two positions is given by

Fig. 16 Example of a LEP chromaticity measurement. (a) shows the applied RF frequency shift and (b) shows the response of the horizontal and vertical betatron tunes measured by PLL tune tracking.
This phase difference is a maximum when \( nQ_s = \frac{1}{2} \), i.e. after half a synchrotron period, giving

\[
\Delta \psi_{\text{max}} = -2 \omega_\tau \Delta \tau
\]

The chromaticity can therefore be written as

\[
Q' = \frac{-\eta \Delta \psi(n)}{\omega_0 \Delta \tau \left( \cos(2\pi n Q_s) - 1 \right)} = \frac{\eta \Delta \psi_{\text{max}}}{2 \omega_0 \Delta \tau}
\]

A schematic layout of the CERN-SPS Head-Tail monitor [10] set-up is shown in Fig. 17(a). A straight stripline coupler (see section 1.1.3) followed by a 180° hybrid is used to provide the sum and difference signals for a given measurement plane. These signals are fed into a fast-sampling (2GS/s on each channel), high bandwidth (2GHz) digital oscilloscope. A VME front-end acquisition crate then retrieves the data via a GPIB link and provides the bunch synchronous timing. Using the “Fast-Frame” capabilities of the oscilloscope the data from the same bunch can be captured over several hundred turns. Fig. 17(b) shows the result of such a head-tail chromaticity measurement. The top two plots show the transverse movement of the head and tail respectively of a single bunch after the beam is kicked. The lower left plot shows the evolution of the phase of the head and tail and the phase difference. It can be seen that the signals are re-phased after one synchrotron period, with the phase difference a maximum after \( \frac{1}{2} \) a synchrotron period. The final plot (lower right) shows the calculated chromaticity (using equation 3.6) for all turns where the phase difference is well defined.

3.3 Coupling Measurement

The control of coupling (the degree to which horizontal and vertical betatron motion is linked) is also important for circular accelerators. Excessive coupling will make tune and chromaticity measurements almost impossible, as the information from both planes are mixed-up in the observed signal. A very good and comprehensive summary of linear betatron coupling can be found in [11].

3.3.1 Closest Tune Approach

For this method, both betatron tunes are measured during a linear quadrupole power converter ramp which crosses the values of the horizontal and vertical tunes. The remaining separation of the tune
traces is a direct measure for the total coupling coefficient |c|. A measurement example from the CERN-LEP, using a phase locked loop tune measurement is shown in Fig. 18. In order to ensure that the PLL keeps tracking both tunes, even when they approach each other, the measurements are performed on two different bunches.

3.3.2 Kick Method

The above method does not allow for diagnostics during machine transitions. A better tool for the measurement of small coupling coefficients, although demanding quite large beam excitations, consists of applying a single kick in one plane and observing the time evolution of the betatron oscillations in both planes. This method is described in Ref [11].

4. EMITTANCE MEASUREMENT

The ultimate luminosity of any collider is inversely proportional to the transverse emittance of the colliding beams. Preservation of emittance and hence emittance measurements are of particular importance in the long chain of accelerators and storage rings of big hadron colliders as the emittance of a hadron bunch is not appreciably reduced through mechanisms such as the radiation damping associated with lepton machines. Good explanations of emittance can be found in Refs [12, 13].

The emittance which includes about 98 % of the beam-particles can be defined as

$$\varepsilon(98\%) = \frac{\text{beamwidth}^2 - \left( \frac{\Delta P}{P} \cdot D_m \right)^2}{\beta_m} = \frac{\text{FWHM}^2 - \left( \frac{\Delta P}{P} \cdot D_m \right)^2}{\beta_m}$$

(4.1)

where FWHM is the measured full width at half height (2.35σ) of the beam, \(\Delta P/P\) the FWHM of the momentum spread, \(D_m\) the value of the dispersion-function and \(\beta_m\) the value of the beta-function at the monitor position.

From this equation one can immediately see that the measurement of emittance depends on many parameters. This limits the accuracy to which emittance can be calculated, which is generally with a precision no better than around 10%. A number of instruments are capable of measuring the beam profile quite precisely, but in calculating the emittance one also relies on knowledge of the beam optical parameters at the place of the instrument and these are often fraught with considerable uncertainties.
4.1 Scintillator and Optical Transition Radiation Screens

Scintillator screens have been used for nearly a century and are the simplest and most convincing device when one has to thread a beam through a transfer line and into and around an accelerator. The modern version consists of a doped alumina screen which is inserted into the beam and can stand high intensities and large amounts of integrated charge. In its simplest form a graticuled screen is observed using a TV-camera. It can deliver a wealth of information to the eye of an experienced observer, but only in a semi-quantitative way. Much can be done about that with modern means of rapid image treatment, but questions concerning the linearity of these screens at high beam densities remain.

Optical Transition Radiation (OTR) screens are a cheap substitute for scintillator screens. OTR radiation is generated when a charged-particle beam transits the interface of two media with different dielectric constants (e.g. vacuum to metal or vice versa) [14]. Since this is a surface phenomenon, the screens can be made of very thin foils which reduces beam scattering and minimises heat deposition. The radiation produced is emitted in two cones around the angle of reflection for backward (vacuum to metal) OTR so that if the foil is placed at 45° to the beam direction, the radiation produced is at 90° to the beam direction. In addition two cones of forward OTR (metal to vacuum) are produced around the beam direction (see Fig. 19). The angular distribution of the emitted radiation has a central hole and a peak located at 1/γ. The higher the value of γ the sharper the peaks and the more light can be collected, which is why OTR is generally suited to lepton or high energy hadron machines.

4.2 SEM-Grids

Secondary Emission (SEM) Grids, also known as harps, consist of ribbons or wires which are placed in the beam. As the beam intercepts the grid, secondary emission occurs leading to a current in each strip which is proportional to the beam intensity at that location. By measuring this current for all strips a beam profile is obtained. SEM-grids are the most widely used means to measure the density profile of beams in transfer lines. In addition, sets of three, properly spaced (i.e. with the right phase advance between monitors), allow a determination of the emittance ellipse. What makes them popular is their simple and robust construction, the fact that there is little doubt about the measured distribution, and their high sensitivity, in particular at low energies and for ions. At higher energies they can be considered semi-transparent. Amongst their drawbacks are the limited spatial resolution (difficult to get the wire spacing much below 0.25mm) and the rather high cost for the mechanisms and electronics.
4.3 Wire Scanners
Of all the instruments used for measuring the emittance of circulating beams, wire-scanners are considered to be the most trustworthy. They come in two different types; rotative and linear. Rotative wire scanners consist of a thin wire (some tens of microns in diameter) mounted on a fork which is attached to a rotating motor (see Fig. 20), while linear scanners use motors which push/pull the wire across the beam. There are two ways of obtaining a beam profile with wire scanners; by measuring the secondary emission current as a function of wire position (similar to the SEM-grid acquisition mentioned above) or by measuring the flux of secondary particles created as the beam interacts with the wire. This latter technique is often used for high intensities, where the heating of the wire produces thermal emission which falsifies the secondary emission results. It relies on the use of radiation detectors, typically scintillators followed by photo-multipliers, placed downstream of the wire scanner to detect the $\gamma$-radiation and secondary particles produced when the wire intercepts the beam. To make the flux collected independent of the wire position may require the summation of the signals from two or more detectors positioned around the beam chamber.

Fast wire scanners are nearly non-destructive over a wide range of energies. Their spatial resolution can reach the micrometer range and, with fast gated electronics, the profiles of individual bunches can be observed. Their great sensitivity also allows them to be used for the study of beam halos.

Fig. 20 Rotative wire scanner and an example of a wire scanner profile measurement.

4.4 Residual Gas and Luminescence Monitors
Rest gas monitors are used in many high energy accelerators in order to reconstruct transverse beam distributions (see e.g. Ref. [15]). The signal results from the collection of either the ions or the electrons produced by the beam ionising the small amount of residual gas in the vacuum chamber. These ions or electrons are accelerated using a bias voltage of several kilovolts and collected on a micro channel plate (MCP). The avalanche of electrons produced by the MCP then hits a phosphor screen, giving an image of the beam profile which can be monitored using a CCD camera (see Fig. 21). Due to their rigidity, ions are less sensitive to the distorting effects of the space charge from the circulating beam, but their slow drift time, even with high bias voltages, means that they spend a long time in this beam field, making it difficult to analyse rms beam dimensions smaller than one millimetre. In order to use electrons to produce an image, a transverse magnetic field needs to be added around which the electrons spiral on their way to the MCP. This eliminates, to a large extent, the space charge effects of the beam and allows sharper images to be produced than with ions. This additional magnetic field, however, is also seen by the beam and has to be compensated by two corrector magnets either side of the ionisation profile monitor.
Luminescence monitors (see e.g. Ref. [16]) also rely on the interaction of the beam with a gas in the vacuum chamber. In this case the gas of interest is nitrogen, in which electrons are excited from the ground state to a higher energy level by the passing beam. Once the beam has passed the electrons return to the ground state and emit photons. In the case of nitrogen the dominant photon wavelength is 391.3nm, corresponding to light at the lower end of the visible range, for which many detectors are available. In general, the residual gas alone does not produce enough photons for accurate imaging and hence a local pressure bump is usually created by injecting a small amount of nitrogen to enhance the photon production. The principle of luminescence monitoring and a schematic layout of such an instrument are shown in Fig. 22. Also shown in Fig. 22 is an example of a continuous measurement performed at the CERN-SPS, showing the ability of such an instrument to track the evolution of the beam size through the various acceleration stages with little effect on the beam.

Most users consider both the residual gas ionisation and luminescence profile monitors to be semi-quantitative and not be relied upon for absolute emittance measurements, even after calibration.
against some other instrument such as a wire scanner. Their virtual transparency for the beam, however, makes them useful for the continuous on-line tracking of beam size.

4.5 Synchrotron Radiation Monitors

Fig. 23 The CERN-LEP BEXE detector based on cadmium telluride photo-conductors.

Synchrotron radiation monitors are limited to highly relativistic particles and offer a completely non-destructive and continuous measurement of the 2-dimensional density distribution of the beam. These monitors make use of the light produced when highly relativistic particles are deflected by a magnetic field. They are therefore usually positioned to make use of parasitic light produced by a dipole magnet in the machine or behind a purpose built “wiggler” magnet in which the beam is deflected several times to enhance the photon emission.

Fig. 24 Tracking vertical beam sizes with the BEXE detector during electron-position collisions.

The most common way of measuring the beam size with synchrotron radiation is to directly image the extracted light using traditional optics and a camera. The spatial resolution for such systems is usually limited by diffraction and depth-of-field effects. If the beam is sufficiently relativistic then the photon emission extends into the hard X-ray region of the spectrum and X-ray detectors can be used, for which diffraction effects can be completely disregarded. Such an instrument, based on
cadmium-telluride (CdTe) photo-conductors, was used at the CERN-LEP [17] to measure rms beam sizes down to 300 μm with a resolution of some 10 μm (see Fig. 23). The detector consisted of 64 voltage biased CdTe photo-conductors of 4 μm thickness and spaced by 100 μm on a ceramic substrate. Each photo-conductor was followed by its own individual charge amplifier. By reading out the signal from each cell the beam profile could be reconstructed. The interesting feature about such photo-conductors is that they allow real-time measurements with data acquisition rates up to 100 kHz. In addition they are extremely radiation resistant, accepting doses beyond 10^{12} Grays. These detectors were heavily used towards the end of CREN-LEP operation to optimise the luminosity by tracking the electron and position vertical beam size during collision (see Fig. 24).

5. BEAM LOSS MONITORING

Beam loss monitors (BLMs) have three main uses in particle accelerators:

- **Damage prevention** - Beam loss may result in damage to accelerator components or the experimental detectors. One task of any BLM system is to avoid such damage. In some accelerators it is an integral part of the protection system, signalling the beam abort system to fire if a certain loss rate is exceeded. This is of vital importance to the new generation of superconducting accelerators, for which even fairly small beam losses in the superconducting components can lead to magnet quenches.

- **Diagnostics** - Another task of BLM systems is to identify the position (and time) of unacceptable beam losses and to keep the radiation level in the accelerator and its surroundings as low as possible.

- **Luminosity optimisation** - BLMs can also help in the tuning of the machine in order to produce the long lifetimes necessary for improved luminosity.

The job of the BLM system is to establish the number of lost particles at a certain position within a specified time interval. Most BLM systems are mounted outside the vacuum chamber, so that the detector normally observes the shower caused by the lost particles interacting in the vacuum chamber walls or in the materials of the magnets. The number of detected particles and the signal from the BLM should be proportional to the number of lost particles. This proportionality depends on the position of the BLM with respect to the beam, the type of lost particles and the intervening material. It also, however, depends on the momentum of the lost particles, which may vary by a large amount during the acceleration cycle. One has to distinguish between two types of losses:

- **Fast losses** – where a large amount of beam is lost over a very few turns.

- **Slow losses** – where partial beam loss occurs over some time (circular machines) or distance (LINAC, transport lines). In storage-rings, the lifetime is defined by slow losses. There are many reasons for these losses and a BLM system is very helpful for finding out what is happening in the machine. In superconducting accelerators a BLM system can also prevent beam loss induced quenches caused by these slow losses.

The fact that BLM systems have to cover both of these cases means that they are required to function over a very large dynamic range, typically in the region of 10^4 to 10^6.

5.1 Long Ionisation Chambers

In 1963, Panowsky [18] proposed a BLM system for SLAC which consisted of one long (3.5 km) hollow coaxial cable filled with Ar (95%) + CO_2 (5%), mounted on the ceiling along the LINAC, about 2 m from the beam. When a beam loss occurs, an electrical signal is produced which propagates to both ends of the cable. Position sensitivity is achieved by comparing the time delay between the direct pulse from one end and the reflected pulse from the other. The time resolution is about 30 ns (~8 m) which, for shorter versions, can be reduced to about 5 ns. This principle of space resolution works for linear accelerators and transport lines with a bunch train much shorter than the machine and with relativistic particles. For particles travelling significantly slower than the signal in the cable the
resolution of multiple hits in the cable becomes difficult. In this case, and for circular machines, it is necessary to split the cable. Each segment has to be read out separately, with a spatial resolution which becomes approximately equal to their length.

5.2 Short Ionisation Chambers

Short ionisation chambers are used in many accelerators (see e.g. Ref. [19]). They are more or less equally spaced along the accelerator with additional units at special positions such as aperture restrictions, targets, collimators, etc. The chamber provides some medium with which the secondary particles created by the beam loss can interact, typically a gas such as nitrogen or argon. This interaction produces electron-ion pairs which are collected by a series of high voltage gaps along the length of the chamber. The resulting current is then measured and is proportional to the beam loss at the location of the monitor. An example of a CERN-SPS ionisation chamber is shown in Fig. 25.

![CERN-SPS ionisation chamber](image)

Fig. 25 A CERN-SPS ionisation chamber used for beam loss monitoring.

5.3 Scintillation Counters

In the case where losses occur in a machine without a full BLM system, a plastic scintillator with photomultiplier readout is often temporarily installed. Such systems have a well known behaviour, but the radiation damage of the plastic scintillator restricts their long term use. Liquid scintillators are not susceptible to such damage and have been installed in some accelerators [20, 21]. Such BLMs can be very fast, with pulse rise times of around 10ns, but suffer from drift in the photomultiplier gain.

5.4 Aluminum Cathode Electron Multipliers

In such detectors the sensitivity of photomultipliers to ionising radiation is increased by replacing the photocathode with an aluminium foil. This foil then works as a secondary electron emitter when irradiated. A BLM system consisting of Aluminum Cathode Electron Multipliers (ACEMs) is installed in the CERN-PS and PS-Booster [22]. It is very fast, with signal rise times in the order of 10ns, but is rather expensive since the ACEM is not a standard tube of photomultiplier manufacturers.

5.5 PIN Photodiodes

For circular electron accelerators which emit hard synchrotron radiation it is difficult to distinguish between the beam loss distributions and the synchrotron radiation background using traditional BLM techniques. In DESY-HERA, an electron-proton collider, the warm electron and a superconducting proton rings are in the same tunnel. Protection of the superconducting proton beam magnets from beam loss induced quenches must therefore rely on a BLM system which sees only the proton beam losses and not the synchrotron radiation background. In this case back to back PIN photodiodes are used to distinguish between the hadronic shower created by beam losses and the synchrotron radiation [23]. The charged particles will interact with both photodiodes, giving a coincidence signal, while the photons will be absorbed by the first diode. In contrast to the charge detection of most other BLM systems, PIN photodiode detection depends on counting coincidences, with the count rate proportional to the loss rate so long as the number of overlapping coincidences is small.
6. LUMINOSITY MONITORING

Luminosity Monitors are specific to colliders, since they measure the collision rate of the two counter-rotating particle beams. The following formulae define luminosity and related quantities:

Luminosity:

\[ L = f_{\text{rev}} \frac{MN^2}{4\pi\sigma^2} \]

Normalized emittance:

\[ \varepsilon_N = \gamma \frac{\sigma^2}{\beta_*} \]

Beam-beam tune shift:

\[ \Delta\nu_{bb} = \frac{N r_p}{4\pi\varepsilon_N} \]

where \(f_{\text{rev}}\) is the revolution frequency, \(M\) the number of bunches, \(N\) the number of particles per bunch, \(\sigma\) the rms beam size at the collision point, \(\beta_*\) the beta function at the collision point and \(r_p\) the particle radius.

Since the counting rates of the experiments are directly proportional to the luminosity, the aim of the accelerator operators is to maximise the luminosity. This can be done by having a large number of particles per bunch, many bunches and small beams sizes at the interaction point.

In this section, luminosity monitoring will be taken as an example of beam instrumentation engineering, i.e. the whole process from selecting an appropriate physics process to system design. The system presently under development for the LHC has been chosen for this case study, as all the documents and figures are easily at hand. The following steps will be treated:

- Functional requirements
- Choice of physics process
- Location of the sensor
- Choice of the sensor

6.1 Functional requirements of the LHC luminosity monitor

The monitor under discussion is aimed at giving a relative luminosity reading for machine optimisation, but it is not required to give the absolute luminosity (as defined above) for the calculation of the underlying cross-section of the experimental physics processes. Hence the system does not need an absolute calibration. In addition, the monitor is to be used to study the variation in luminosity between the individual bunches of the LHC. This means that the detector has to have the bandwidth of the individual bunch crossings, which is 40 MHz. The expected difference in luminosity between bunches is very small, so a resolution of 1% is required.

6.2 Choice of the physics process for the detector

Since any count-rate coming from the collision point of the beam particles can be used as a signal for luminosity monitoring there is a wide choice of physics processes that could be used for this measurement. Due to both cost and integration issues the detector has to be small in size, hence huge detector arrays covering a large solid angle of secondary particle production can be excluded. This eliminates all well identified physics processes producing particles with large transverse momenta. Diffractive beam particle interactions, for which at least one of the incoming protons dissociates into a leading (high energy) neutron plus other secondary particles have therefore been considered as a source for the luminosity signal. Due to the nature of this process, most of the secondary neutrons are emitted into a very small solid angle in the forward direction. The properties of this interaction are pretty well known from lower energies, so that the cross section can be assumed to within a 10% accuracy. This process has been chosen as the basis for LHC luminosity monitoring.
6.3 Location of the sensor

Since the neutron production is in the very forward region, a monitor located close to the interaction point would have to be inside the vacuum chamber. In order to measure the forward neutron flux outside the vacuum chamber one also needs at least one intervening deflecting dipole to bend away the charged beam particles. Looking at the design of one of the high luminosity LHC interaction regions (Fig. 26) one can spot two large metallic objects, which are introduced to shield the superconducting elements from the particle flux of the collision products. The TAS is intended to shield the inner triplet from secondary particles, while the TAN is designed to absorb the forward neutron flux, which is just the signal required for luminosity monitoring.

Fig. 26 Layout of one of the LHC interaction regions.

Fig. 27 shows the simulated secondary particle flux at location of the TAN. The circles indicate the location of the two beam pipes. If the neutron flux (centre image) is weighted with the average particle energy, it becomes the dominant signal at this location. The luminosity detector will therefore be located inside the TAN (a 4m long copper block) between the two beam pipes.

Fig. 27 Simulated secondary particle flux distribution at the location of the TAN.

6.4 Choice of the sensor

Having selected the location, the physical dimensions of the detector are limited by installation constraints. Moreover, since the TAN absorber is designed to shield the superconducting elements from an enormous flux of secondary particles, the luminosity detector will have to withstand a very high radiation dose. If one assumes 20 years of operation at nominal luminosity, the integrated neutron flux will be \(10^{18}\) n/cm\(^2\). This is about 3 orders of magnitude larger than normal so-called “radiation hard” semiconductor sensors can withstand. It should also be kept in mind that after some running time the whole installation will be so radioactive, that human intervention for repair will be nearly
impossible. This, in addition to the other stringent requirement of a bandwidth of 40MHz meant that only two different detector technologies were retained and studied in detail:

1. A polycrystalline cadmium telluride (CdTe) detector array [24]
2. A pressurised ionisation chamber with continuous gas exchange [25]

The first option has the advantage of high bandwidth, but the radiation hardness is not completely demonstrated. The second option is believed to withstand the high radiation levels but, even after some years of optimisation, the bandwidth is still somewhat too low. Due to the high radiation doses expected, however, the most likely choice will be the ionisation chamber. Fig. 28 shows the design of the ionisation chamber presently used with test beams.

Fig. 28 Schematic of the ionisation chamber for LHC luminosity monitoring.

6.5 Electronics

The most critical element in the system is the detector itself, due to the requirements for bandwidth and radiation hardness. Once a signal is produced, it will be sent out of the TAN block via special radiation hard cables (stainless steel with a mineral insulator) to standard preamplifiers and digitising electronics. The signals will be recorded for each individual bunch crossing and averaged over many machine turns in order to produce the luminosity information for the control room.

7. SOME EXAMPLES OF BEAM DIAGNOSTICS

This section is meant to serve as general entertainment for those readers who have made it to here with their reading! Two examples from CERN-LEP operation have been selected, and show how difficult it can be to interpret primary measurements and decide on the right actions for solving a problem in an accelerator.

7.1 The CERN-LEP beam does not circulate!

The schedule for the CERN-LEP accelerator had a very regular structure. Every year LEP was used for about 8 months for physics beams followed by a 4 month maintenance and upgrade shutdown. During this shutdown major intervention work was sometimes carried out on the machine. At the next start-up it was therefore often expected that typical problems such as inverted magnet polarities would have to be overcome. One year, the start-up was particularly bad, with neither the electron beam nor the positron beam capable of being injected and made to circulate. Several hours were used to check all vacuum conditions, power supply currents, settings of the radio frequency system, injection deflectors
and so on, but nothing indicated a severe problem. Finally people started to look in detail at the measured beam trajectory from the injection point onwards. A typical example for the positron beam is shown in Fig. 29.

![Fig. 29 Measurement of the LEP phase advance when beams did not circulate.](image)

What is actually shown in Fig. 29 is the phase advance from one beam position monitor to the next, as calculated from the measured beam trajectory. At a particular quadrupole (QL10.L1) the regular pattern is distorted. Additional measurements also indicated that most of the beam was lost at this point. The first conclusion was to suspect a problem with this quadrupole. People went in, measured the current in the quadrupole, checked its polarity, inspected its coils, but could not find anything abnormal. The indications of the beam measurements, however, clearly pointed to a problem at this location. After many discussions and potential hypotheses it was decided to open the vacuum chamber. It should be noted that this was a major intervention, causing a stop of the accelerator for at least one day. One can understand the surprise of the intervention team when they looked into the open vacuum chamber and saw a beer bottle!!!

During the shutdown intervention, somebody had sabotaged the LEP accelerator and had inserted a beer bottle into the beam pipe (Fig. 30)! What had upset the operation team most at the time was the fact that it was a very unsocial form of sabotage - the bottle was empty!

![Fig. 30 The mystery of the beam circulation problem in LEP is solved!](image)

7.2 The beam gets lost during the beta squeeze

This again is one of the stories from LEP operation which took several hours of beam diagnostics to solve. The problem in itself is pretty complex, and therefore requires some additional explanations beforehand.
The acceleration of the particle beams and the change of the lattice function in the insertion regions in order to get smaller values of the beta-function at the crossing point (hence higher luminosity) are so called “dynamic processes”. The presence of the beam requires that all actions are well synchronised. For example, the power converters of all relevant magnetic circuits have to be controlled such that beam parameters like the closed orbit, tunes and chromaticities stay within tolerance during the dynamic process. In order to achieve this, the behaviour of these beam parameters is periodically measured as a function of time and the corresponding power converter tables are updated.

During one period of LEP operation it was found that the beams were lost during the beta squeeze. Shortly before the total loss of the beams a significant beam loss was measured. As standard practice when encountering such problems, the engineer in charge (EIC) launched a new machine cycle with diagnostics facilities such as “tune history” (the measurement of the betatron tunes as a function of time – see Section 3) switched on. This indicated that the vertical tune moved out of tolerance during the beta squeeze. Fig. 31 shows an excerpt from the actual LEP logbook entry of this event.

As a result of this observation, the EIC launched another cycle, but inserted a breakpoint (to stop the accelerator cycle) just before the critical moment in the beta squeeze when the deviation in tune occurred. Having reached that breakpoint the tunes were measured statically and found to be perfectly within tolerance. The beta squeeze was then executed step by step, and to the big surprise of the operations crew, the tunes were found to be correct at all times. The beam had passed the beta squeeze like on an ordinary day! But on the next attempt, without a break in the cycle, the beam was again lost at the same moment, and several people scratched their heads to find an explanation.

Finally, the following measurement was made. The machine was prepared and a breakpoint again inserted just before the critical beam loss. Once this point was reached, the EIC requested the execution of one further step in the beta squeeze. The facility by which one could execute a single step in a dynamic process had the additional feature that one could specify the rate of current change of any machine element. This current rate limitation was changed from 25A/s (nominal) down to 2.5 A/s on consecutive steps. The corresponding tune history (the result from the vertical plane is plotted on the lower graph) is shown in Fig. 32.

One can clearly see that a huge (negative) tune excursion occurred when the step was executed at the nominal rate. This observation led the EIC to the right conclusion, which was that one of the power supplies was able to deliver the demanded current statically, but not dynamically. When this
was discussed with experts from the power converter group, they indicated that the power supplies for the superconducting insertion quadrupoles were built as two blocks in series, each of them able to deliver the necessary current (each block typically 1000 A/10 V). Both of these blocks were required to have enough voltage margins to enforce a current change against the inductance of the quadrupole coil. This then explained the whole story. One of these blocks was faulty, but since the power converter could deliver its (static) current, it was not detected by an alarm or surveillance circuit. In the static case the working, single block could deliver the requested current. If the dynamic rate was too high, however, this single block could not provide enough current leading it to lose synchronism with the other power converters. This resulted in the large tune change observed and ultimately the total beam loss.

Fig. 32 The LEP tune history during the beta squeeze for various power converter ramp rates.

These two examples show the enormous potential of beam instrumentation if they are used in the right combination by intelligent people.

REFERENCES


C. Bovet et al., “Measurement Results with the BEXE Detector at LEP”, 3rd European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, DIPAC ’97, Frascati, Italy, Oct 1997.


