BEAM CHARGE MEASUREMENTS

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Abstract

The measurement of beam charge is fundamental to all particle accelerators. There exist many methods to achieve this, which can broadly be classified into two categories: intercepting measurements, which are destructive for the beam and result in absorption of a significant amount of energy and non-intercepting measurements using electric or magnetic field coupling. In both categories one can find instruments that process the beam signals with high dynamic range, both in amplitude and time. The aim of this article is to present the current state of beam charge measurement technologies. Various measurement methods will be described with their uses, advantages, and the achievable resolution and accuracy will be discussed. The technological problems related to their fabrication will also be addressed.

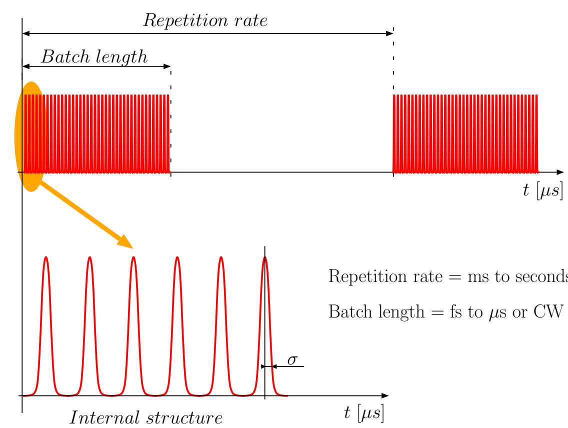


Figure 1: CERN LINAC II: RR=900 ms, BL=200 μs typ.

INTRODUCTION

Effective control of an accelerator requires numerous types of diagnostic tools. The tools providing an information about the beam parameters are called *beam diagnostics*. They include many measurement techniques which could be grouped into two major branches:

- *Intercepting measurements*, which are destructive for the beam, or they result in absorption of a significant amount of its energy. These include e.g. wire scanners, Secondary Emission (SEM) grids, Optical Transition Radiation (OTR), scintillator, and a few techniques of beam charge measurements such as Faraday cup measurement.

- *Non-intercepting measurements*, which use electric or magnetic field coupling of beam to the measuring instrument. These include e.g. beam position monitors, synchrotron light monitors, beam loss monitors, luminosity and tune measurements, and capacitive or inductive beam charge monitors (either AC or DC).

Beam charge measurement (also called *beam intensity measurement*) is a process whose result is an information about a number of particle beam's charges. The directly measured quantity is often beam current, the number of charges is a calculated value. An integral of the measured beam current over a specific region of interest (ROI) results in a beam charge. Number of charges in such a region is expressed as the beam charge divided by the elementary charge.

The term *ROI* is dependent of the context in which the measurement is applied: e.g. for the LINACs, the ROI would be the batch length and the intensity measurement would result in an *equivalent DC current* of the particle batch generated (Fig. 1). Different situation would be in the case of free electron-laser (FEL) or hadron machines, where the major interest is in measurement of a single bunch charge, and hence the ROI would be equal to few sigmas, providing that bunch spacing is sufficient.

The beam intensity measurement is used to define the intensity loss at injection, acceleration and extraction. Slow charge loss measurement provides information about lifetime of the circulating beam, and it can be used to protect the machine or humans against machine malfunctions. Number of charges enters also the luminosity equation.

Most critical demands for the beam charge measurements are related to the measurement accuracy and dynamic range. High accuracy and high bandwidth of the measurement is required to measure individual bunches. Precision and speed are needed to calculate the beam lifetime. Currents ranging from several kilo-amperes in induction LINACs to some nano-amperes, as e.g. in CERN's anti-proton decelerator, are measured. The bandwidth of the measurement device is determined by the properties of the measured current. The bunch spacing mainly affects the high-frequency (HF) cut-off, while the revolution period defines low-frequency (LF) cut-off requirements. E.g. the CLIC Test Facility 3 (CTF3) requires bandwidth greater than 7 GHz [1] should the bunch structure be measured.

CHARGE MEASUREMENT SYSTEM

A crucial part of the beam charge measurement system is the device which couples to the beam and provides the signal approximating the beam current. The most used DC intercepting devices are the Faraday cups. The non-intercepting AC devices – electrostatic pickups,

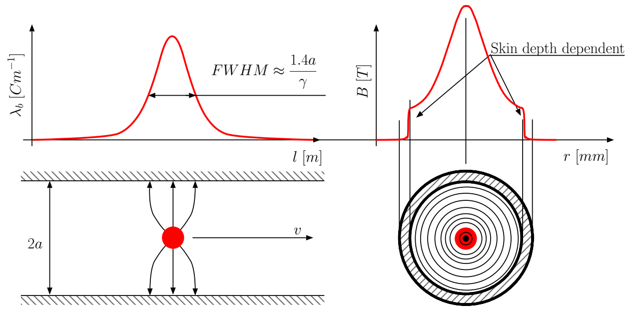


Figure 2: Distribution of the mirror charge and flux lines

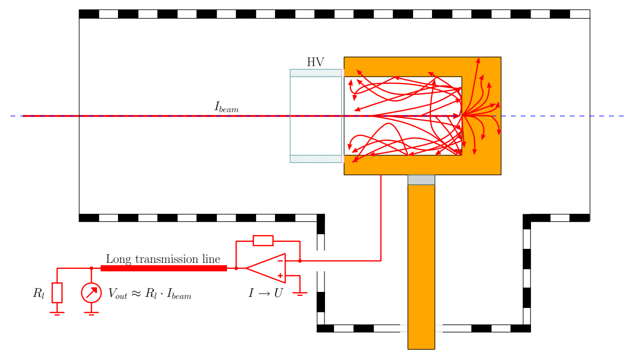


Figure 3: Principle of operation of the Faraday cup

Wall Current Monitors (WCMs) and Fast Beam Current Transformers (FBCTs) – can measure the charge by integration of the beam current or the wall image current coupled inductively or capacitively to the measurement device. Non-intercepting DC devices such as DC current transformers (DCCTs), superconducting quantum interference devices (SQUIDs), and cryogenic current comparators (CCCs), provide charge information based on a magnetic feedback established with the beam. Magneto-resistive (MR) sensors, widely used in clamp-on high current meters, can provide low-precision DC beam measurements.

Beam Signal Interception

In order to understand how the beam signal can be intercepted a concept of Wall Image Current (WIC) must be introduced: Any moving charged particle creates an electro-magnetic field. Should the particle move at relativistic speed inside the vacuum chamber, its electric field contracts in the direction of motion. An image charge of opposite sign is induced at the inner diameter of the vacuum chamber (Fig. 2). It is dragged as the particle moves, creating the Wall Image Current (WIC), and effectively cancelling the electric field outside of the conducting vacuum chamber. The magnetic part of the particle's field gets strongly attenuated when the flux lines pass through a non-magnetic conductor. The attenuation factor is specified in terms of skin-depth lengths for a particular frequency. Each such length corresponds to an attenuation of ≈8.7 dB [2]. Due to this high-resolution measurement devices can only be installed either in the vacuum chamber, or outside of the vacuum chamber, if an alternate path for the WIC is provided. The device then can couple directly to the electromagnetic (EM) field produced by the beam.

The following paragraphs discuss the devices used to intercept the beam. Only a single candidate from the intercepting measurements is presented: the Faraday cup. All other intercepting methods are rarely used for the beam charge measurements. Discussion then continues in the field of the non-intercepting AC and DC measurement devices.

THE FARADAY CUP

The principle of operation of the Faraday cup is shown in Fig 3. In order to measure the beam charge a *cup* made of a conductive material is inserted into the beam path. When the beam hits the cup, all the collected charge is discharged by the current-to-voltage converter. The detected signal is processed by an integrator to estimate the beam charge.

Faraday cups provide DC measurements and serve as an absolute calibration standard, which can be used to cross-calibrate other measurement equipment. They are usually used for low current measurements due to the cup heat-load: high beam current measurements require actively cooled cups, which considerably increases the design complexity. Important issue is the emission of the secondary charged particles during the impact. This increases the measurement accuracy uncertainty and must be suppressed. One of the methods to do so is to increase the cup length [3], so all the secondary charges are collected back to the cup. Other possibilities are to use either a high voltage (HV) guard ring acting as an electrostatic shielding, or a dipole magnet forcing the charges to spin not letting them to escape from the cup [4]. Should the fast beam structure be observed with high time resolution the signal transmission bandwidth must be extended to GHz range. Standard coaxial-type connection of the cup to the transmission line provides up to hundreds of MHz bandwidth. Bandwidth up to tens of GHz is obtained using *Fast Faraday Cups* [5]. Carefully designed devices can provide measurements in pA range with resolution of 2 fA [6].

NON-INTERCEPTING MEASUREMENTS

AC Measurements

The non-intercepting devices measure the charge by integration of the beam/wall image current. The beam signal is EM coupled or conducted to the measurement device.

Capacitive coupling is mostly used by electrostatic pick-ups sensitive to the charge density. To obtain a measurable signal, the pick-ups use a conductive electrode inserted into the vacuum chamber (Fig. 4). The electrode is isolated and it is subjected to a charge deposit caused by moving parti-

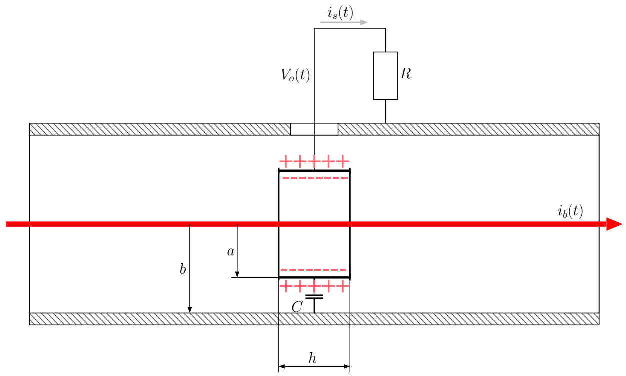


Figure 4: Principle of operation of capacitive pick-up

cles. The voltage difference between the electrode and the vacuum chamber creates a current flowing through a load resistor R.

The resistor R and the capacitor C define the device's LF cut-off. The value of capacitor is given by the sum of the electrode and external capacitances. Due to the LF cut-off the measured signal does not contain a DC component and the signal exhibits a "droop", resulting in a *displacement* of the signal's base line. Hence a proper base-line restoration (BLR) may be required. The signal processing is common to all non-intercepting AC measurements as well as to Faraday cups, and is discussed further.

Splitting the cylinder electrode into four orthogonal electrodes an electrostatic Beam Position Monitor (BPM) is created. BPMs can be used to provide an intensity-suitable measurable signal by summing the signal of the four electrodes, which suppresses the signal first-order position dependence. Third and fifth order position dependence can be eliminated by appropriate mathematical treatment.

To provide a high-bandwidth charge measurement a Wall Current Monitor (WCM) can be used (Fig. 5). The bandwidth of the device often exceeds 5 GHz [1] while maintaining its LF cut-off bellow hundreds of kHz. The WCM conducts the WIC and acts as a current divider providing separate paths for HF and LF WIC components. The HF current passes through a load resistor connected in series with the vacuum chamber. To install the resistor the vacuum chamber must be split, and separated by an isolating gap. A low-impedance bypass installed over the gap then provides an impedance-controlled environment. The device's LF cut-off is proportional to the impedance ratio of the HF and LF paths. Within the measurement bandwidth the WCMs offer an exceptional sensitivity (e.g. comparison of 1 Ω loaded WCM's noise to FBCT's toroid magnetic noise) at the expense of higher LF cut-off. It is believed that the beam position dependence of WCMs is more favourable when compared to toroid measurements due to the distribution of the load resistance homogeneously around the ceramics. The WCM intensity measurement is used e.g. in Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) [7].

Measurements of a beam signal down to a Hz range are

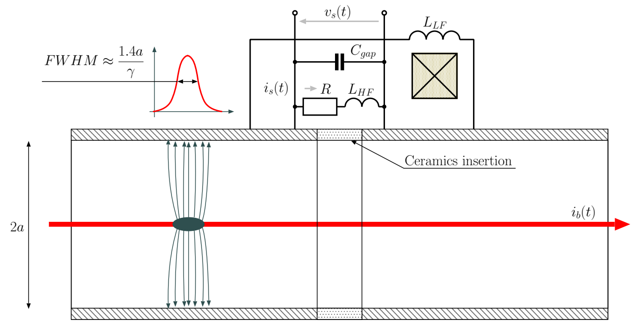


Figure 5: Wall Current Monitor principle of operation

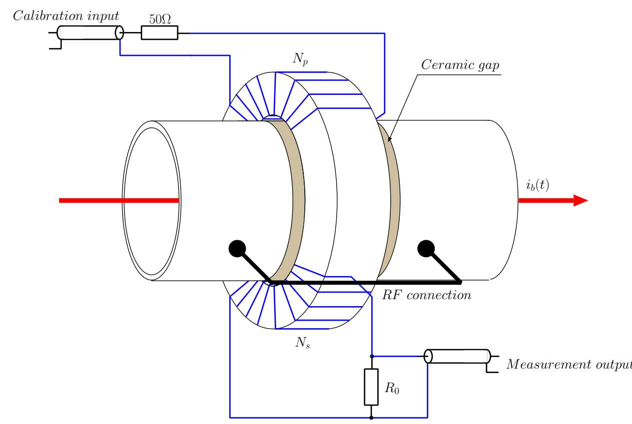


Figure 6: Fast Beam Current Transformer (FBCT)

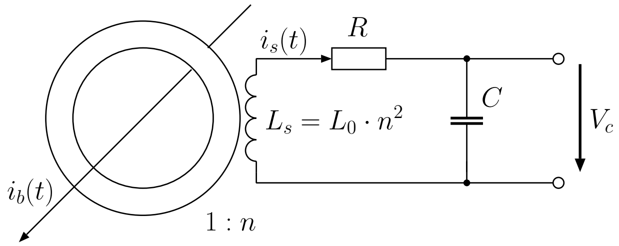
mainly a domain of the FBCTs which offer a bandwidth of few Hz up to a GHz. In contrast to all previously discussed measurement methods, they can be absolutely calibrated.

The principle of the measurement using an FBCT is shown in Fig. 6. A toroidal transformer is used to measure the beam current. As in case of the WCM the WIC is diverted using a ceramics insulator to an external low impedance Radio Frequency (RF) connection. The *LF cut-off* of the FBCT is given by the winding inductance. The *HF cut-off* is limited by a capacitive coupling between the turns, stray and eddy currents, the energy loss in the core material and the loss of permeability with the frequency. Modern materials such as amorphous cobalt-based alloys achieve cut-off frequencies up to 2 GHz.

The primary winding of the FBCT is formed by the beam. Often two secondary windings are installed: a calibration turn used to inject a known current into the transformer, and a measurement winding connected to an acquisition system and providing the measurement signal.

The FBCT droop effect can be well controlled in the transfer lines, where the repetition rate of the measurement is small compared to the FBCT LF cut-off time constant. To measure high duty cycle circulating beams, usage of BLR techniques is essential in order to perform the measurement. Selection of proper BLR method depends much on the characteristics of the beam.

The FBCT works in two operational modes depending of



$$I(t) = c_1 e^{-\lambda_1 t} + c_2 e^{-\lambda_2 t}, \lambda_{1,2} = \frac{R}{2L_s} \pm \sqrt{\frac{R^2}{4L_s^2} - \frac{1}{L_s C}}$$

Figure 7: FBCT equivalent lumped element circuit

whether the coefficients $\lambda_{1,2}$ (Fig. 7) are complex or real. In the first case the capacitor C provides a charge storage, discharged once the beam passes the FBCT aperture. The amplitude of the resonant capacitor discharge is proportional to the number of charges measured [8]. In the latter case the FBCT acts as an ordinary impulse transformer, providing a signal proportional to the beam current.

Currently achievable measurement resolution for hadron machines is approximately 2–3 pC RMS. This is not sufficient for electron machines as very short pulses of few tens of pC must be measured. Recent studies show that a careful design of the electronics front-end can lead to a significant reduction of the RMS noise and hence in the laboratory conditions a resolution of ≈0.01 pC is achievable [9]. Such resolution is however deteriorated by EM interference once the device is installed in the machine.

Recent discoveries on the field of the FBCT technology reveal also important issues related to transversal beam position dependency of the measured signal [10].

Electronics processing chain and calibration: The beam signal acquired by the AC devices must be further processed to get the charge information. The usual signal path consists of an amplifier/attenuator section, followed by an Analog to Digital Converter (ADC), BLR and integrator. The latter two processings are performed numerically, which enables usage of advanced signal processing methods such as deconvolution of the measured signal to improve the LF cut-off. BLR is based on the knowledge of the beam signal properties (e.g. injection scenario), or on usage of sample-and-hold/peak detectors to recover the DC signal component. Integration can be performed as a standard sum of the sampled signal, or if required it may use interpolation to increase the calculus precision. In cases where the ADC performance is not satisfactory, an analogue integration may be used. Analogue integrator design requires more attention, as additional effects, like input offsets, integrator non-linearity, bandwidth and slew-rate limitations, must be considered. Usage of analogue integrators usually results in much lower bandwidth requirements put on the ADC chain.

For proper operation the intensity measurement system must be calibrated. Calibration is a process of matching

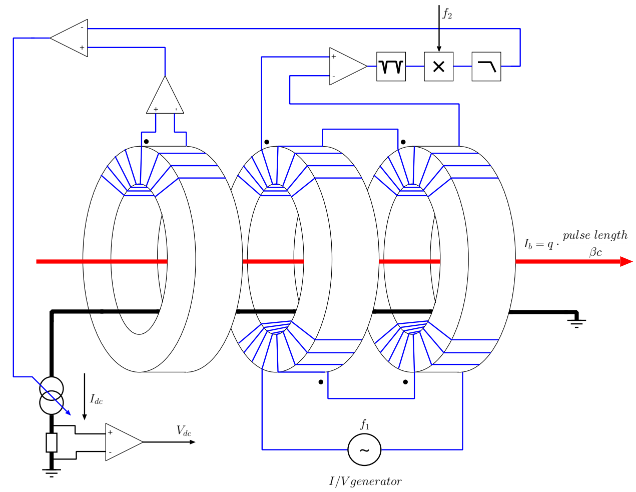


Figure 8: DC current transformer (DCCT) - principle of operation

a reference signal measurement to the reference value. If the reference value is not known, it must be measured with better precision than provided by the measurement system being calibrated. A properly calibrated system provides compensation for systematic errors caused by fabrication processes and tolerances of components. From the above described methods only FBCTs can be directly calibrated. All other methods can calibrate the electronics processing chain, however they do not offer a possibility of calibrating the measurement track completely, and hence rely on indirect calibration by using either Faraday cups, FBCTs or DCCTs. Two basic types of calibration are used: a pulsed current source, or direct charge calibration. While the first one is using a true current source, which is able to precisely generate pulses of specific amplitude (few mA to A) and width (ns to µs), the second method uses capacitor as a charge storage. The fully charged capacitor is discharged into the calibration winding of the FBCT. Typical absolute accuracy of both calibration methods lies somewhere between 1 to 5 % of the measurement full scale (FS).

DC Measurements

A device used to measure an intensity of a circulating beam down to DC is the DC current transformer (DCCT). The principle of operation is shown in Fig. 8. The measurement device uses a “magnetic modulator” to obtain a signal proportional to the DC current of the beam. Magnetic modulation is done by superposition of the magnetic flux generated by a signal generator (through a winding) with the one generated by the beam signal. The windings configuration is such that the current generates in both cores a flux of opposite direction. A common sensing winding provides an output signal. Assuming perfectly matched cores the second harmonic in the output signal cancels due to symmetric excitation by modulation current (Fig. 9 middle). A beam passing through the aperture of the cores creates an

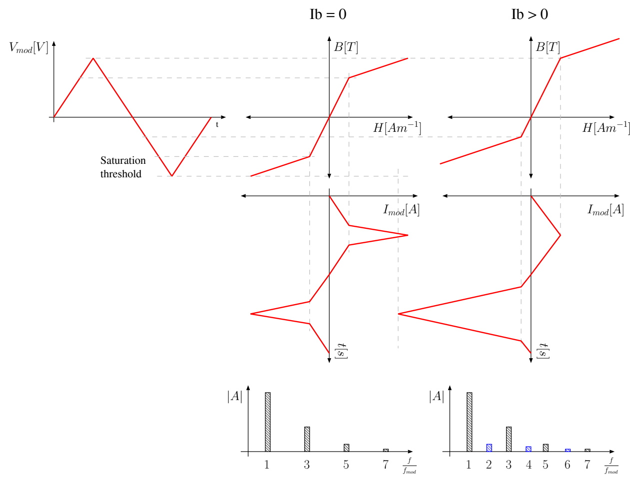


Figure 9: 2^{nd} harmonic production in the DCCT

additional flux. This unbalances the excitation hence even harmonics appear in the output signal, particularly the second harmonic. The second harmonics of the output signal synchronously demodulated to base-band provides a driving signal for a current generator. The generator acts to suppress the flux generated by the beam current. The amplitude of the needed current corresponds to the beam current [11]. An additional AC transformer extends the bandwidth up to ≈50 kHz. This results in faster response of the measuring device to current changes.

The choice of the modulation frequency depends of the used toroid's material and is usually in the range of few hundreds Hz to few kHz. The modulator must provide enough power to drive the cores into saturation. Its frequency spectrum purity is important to avoid superposition and aliasing of the generator's spectra with the measured signal. The reaction time of the feedback loop is usually some tens of microseconds.

The DCCTs provide the full-scale DC beam current measurements in any range from 10 mA to 100 A with resolution down to 1 µA, and dynamic range exceeding 100 dB. Currently, the limit on the measurement precision is imposed by the Barkhausen noise related to the size of the toroid material's magnetic domains, and drifts in the electronics and calibration source used. Typically achieved accuracy is ±500 ppm plus resolution, limited by the absolute accuracy of the calibration standard.

The DCCTs suffer from a long-term zero drift, mainly caused by the electronics temperature dependence (≈5 µA/K). The measurement errors can also be caused by stray fields of surrounding magnets intercepted by the device. The DCCT fabrication involves many technological issues, mostly related to the magnetic material procurement and matching of the B-H curves of the used toroids. Typically used materials have to have high permeability and must be annealed to achieve low coercive fields ($H_c \approx 1\ Am^{-1}$). Suitable types are e.g. Vitrovac 6025 and Metglas 2705M. These are also used to fabricate the FBCTs.

DCCTs are calibrated by injecting a known DC current into the DCCT's calibration turn encompassing all three toroids. Commercially available DC current sources as Keithley 224 or Yokogawa GS200 are used. They typically provide an accuracy better than (±0.05 % of setting + ≈5 µA).

A summary of DCCT technology can be found e.g. in [12], performance limitations are discussed in [13] and [14].

Recent developments on the field of magnetic sensors permit their usage in DC beam current measurements. The measurement devices use either SQUIDs or MR sensors. The SQUIDs can measure extremely weak magnetic fields (tens of fT) with very low noise floor (3 fT $\sqrt{Hz}$). They require temperature controlled environment: low-temperature SQUIDs below 10 K, whereas high-temperature SQUIDs only 70 K [15]. The low-temperature SQUIDs are used in cryogenic current comparators (CCCs). Further information can be obtained in reference [16].

DC current measurements can be provided as well by MR sensors, widely used in on-clip current meters. Nowadays MR sensors' commercial availability makes them attractive for the accelerator technology industry. A study for the GSI-FAIR project has been made of their suitability for the beam current measurements [17].

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