Beam current and beam lifetime measurements at the HERA proton storage ring

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Abstract:

Accelerators with superconducting magnets have special requirements for beam current measurement. Two different systems to measure beam current in the HERA proton ring are presented: a.) A Parametric Current Transformer (d.c to 100 kHz) measures the total circulating beam current in the ring and provides the absolute calibration. b.) The Bunch Current Monitor is a specialized system for low values of beam current. It features an Integrating Current Transformer as a beam sensor and signal processing with a new combination of charge amplifier and dual gated integrator to restore the d.c. baseline reference. The large dynamic range and high resolution permit fast beam lifetime measurements at low values of beam current.

Introduction

The HERA proton ring, with a circumference of 6.3 km, belongs to the new generation of accelerators and storage rings. It uses superconducting magnets for a design energy of 820 GeV. Superconducting magnets are very sensitive to interactions with a particle beam and have to be protected. A localized loss of only 10^9 - 10^{10} protons in the accelerator could cause a quench of magnets, leading to the breakdown of the magnetic field. The consequence would be the total loss of the stored beam, with possible permanent damage to machine components, or at least the loss of many hours or days of machine time. A very sensitive and reliable beam current monitoring system is therefore required. For additional protection, beam loss monitors are distributed in large numbers around the ring. They will give an early warning in case of excessive beam loss and may trigger the beam dumping system.

It is important for HERA operation to minimize this risk of critical beam loss. For this reason, beam currents are kept low during the setting up of the accelerator. A beam with only 1 - 10 proton bunches of low intensity (100 µA - 2 mA average current) is used for the first injections into the ring. High energy physics experiments in HERA require up to 210 circulating bunches of high intensity, spaced in 96 ns intervals. This will lead to the design value of the proton beam current which is 160 mA.

The beam current monitoring system has to measure the total circulating beam current with reliable absolute accuracy and to determine the beam lifetime very quickly, ideally in less than 1 second. In addition, the charge (number of protons) of each individual bunch and the lifetime of any particular bunch or group of bunches should be measured independently.

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It is not possible to meet all these requirements with a single type of beam instrumentation. Different technologies are therefore used to obtain optimum results for specific tasks.

A description will be given of the 2 new beam monitors which measure average beam current in the HERA proton ring. There are 3 other systems which should just be mentioned here, although they are not part of the present report:

1.) The bunch and beam lifetime measuring system[1] which was developed[2] for the electron machines PETRA and DORIS II at DESY. This equipment works well, corresponding to the specification of the original application. It covers the most urgent needs of early HERA operation and reduces time pressure on new developments.

2.) A wall current monitor covers the frequency range from 100 kHz to 4 GHz. It uses a Tektronix Transient Digitizer (SCD 5000) to measures the longitudinal structure of the beam, the shape of the bunches and the filling of the buckets.

3.) A new type of bunch intensity monitor is under development. It is based on a beam current sensor with considerably improved high and low frequency response and signal processing with baseline clamping (once per turn) to restore the d.c. baseline reference. Every circulating bunch in HERA will be digitized and recorded over a large number of revolutions. This will be the subject of a future report.

The Parametric Current Transformer

A Parametric Current Transformer (PCT)[3,4] is used as d.c. beam current monitor in the HERA proton ring. This is an improved version of the zero flux current transformer[5], the combination of active current transformer and magnetic modulator (with parametric amplification) in a common feedback loop. Together with some other products, the PCT was a result of a collaboration[6] and technology transfer between CERN and industry and is now commercially available. The PCT in HERA has 2 current ranges (0 to 20 mA/ 0 to 200 mA) and covers a frequency range from d.c. to 100 kHz. It provides the absolute calibration for all beam current measurements. The measurement of the total circulating beam current is independent of any bunch structure. There is no need for external synchronization or timing which could influence the readings.

The PCT measures a current by effectively compensating the magnetic field of the particle beam. As the loop gain for this feedback is very high, the calibration is stable and the linearity very good. Independent tests have verified a linearity error of less than 0.002% and a calibration error of less than 0.1 % (at 200 mA).

At the lower end of the scale, PCT resolution is limited by "magnetic" noise and zero drift of the magnetic modulator and variations of external magnetic fields.

The large dynamic range of the PCT ($\geq 2\times10^5$ in this application) demands special consideration for the analog to digital conversion. A 7-digit integrating system voltmeter (Solartron 7081, integration time 400 ms) is used and interfaced through GP-IB with the local PC controller (Fig. 1).

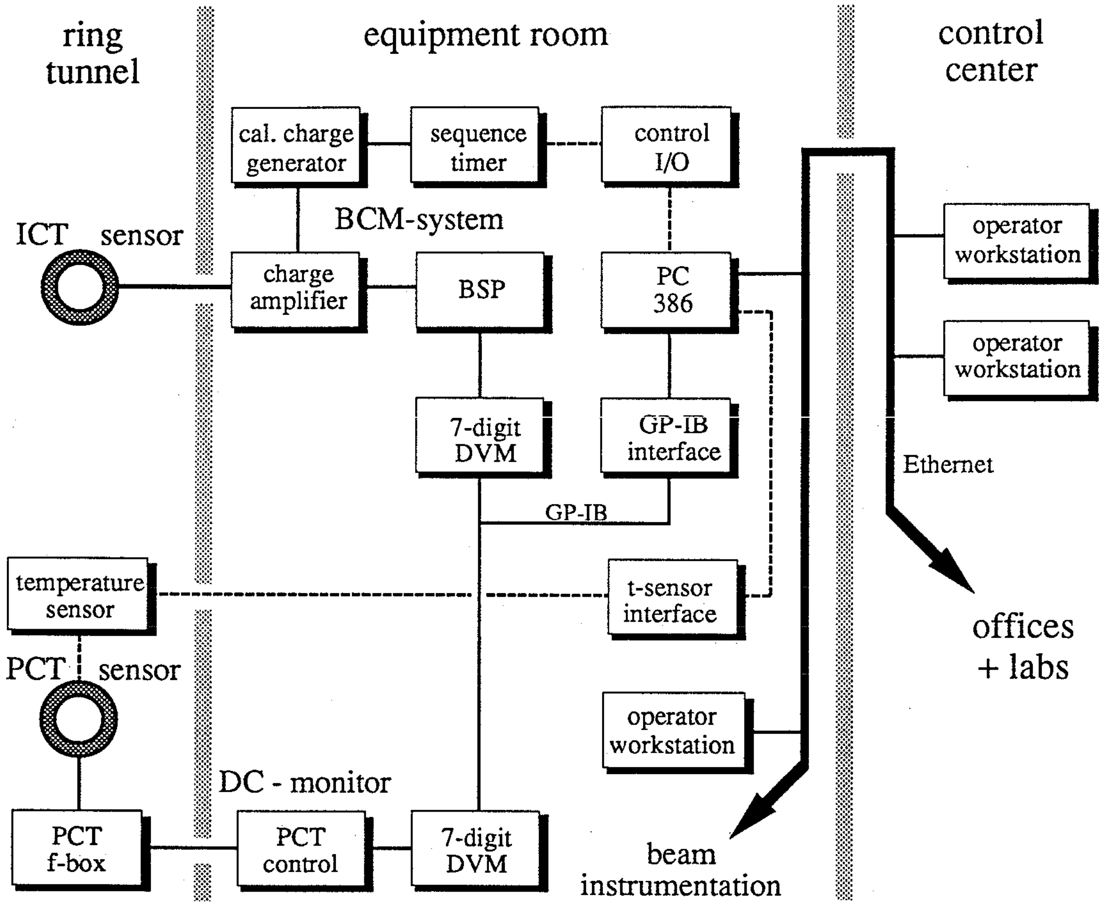


Fig. 1 Beam current monitoring system of the HERA proton ring. Connection with dashed lines are proposed future extensions.

The Bunch Current Monitor

The Bunch Current Monitor (BCM) is a specialized system, designed to work with a single circulating bunch, or a group of up to 10 bunches (Fig. 1). The beam current sensor for the BCM is the Integrating Current Transformer (ICT)[6] described in previous reports[3, 5]. The fast bunch signal (duration ~1 ns) is first stored in a bank of distributed capacitors inside the ICT and then slowly discharged into its output load resistor. The charge collected is exactly proportionally to the charge of the bunch. Internal losses are negligible and most of the errors of conventional current transformers are eliminated.

The analog signal processing chain is designed to handle more than 100 dB of dynamic signal range (without range switching) and to provide high sensitivity. The first element in this chain is a charge amplifier with special design features (Fig. 2). This amplifier should be as fast as possible, but must be protected from signal transients which are too fast for linear response. The input stage (A_1) is a feedback amplifier (custom built hybrid circuit), with a high gain bandwidth product (900 MHz), very low input noise (0.002 $\mu V/Hz^{-2}$), and high current (50 mA) drive capability.

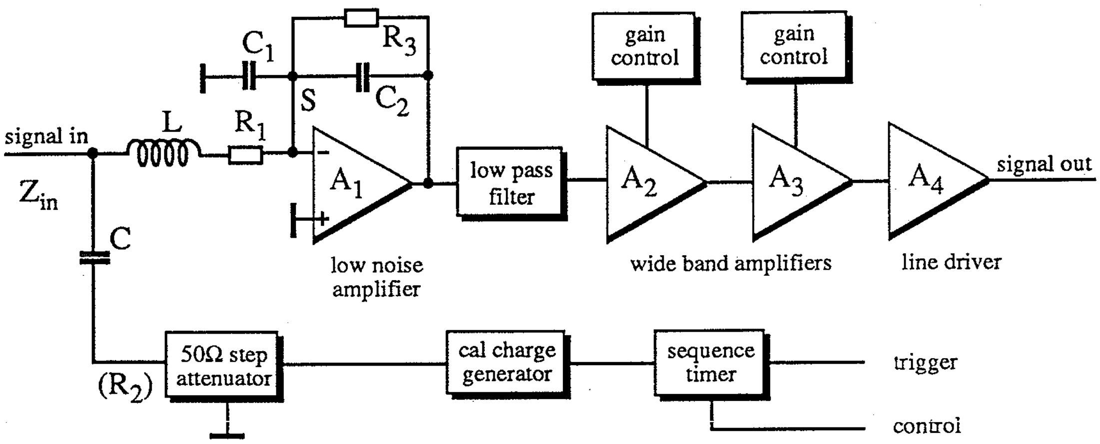
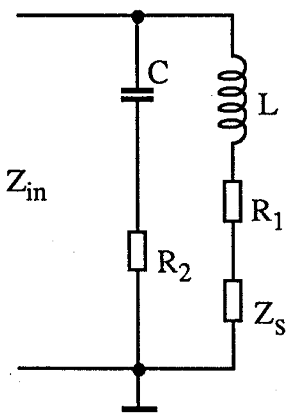


Fig. 2 Simplified diagram of charge amplifier

The maximum slew rate of this hybrid amplifier is very high (300V/μs), but still not fast enough to prevent distortion and nonlinearity with large amplitude bunch signals. To avoid these errors, a passive low pass filter (L; R_1; C_1) is used to reduce signal transients to a safe value well below the slew rate limit of the amplifier. The special trick is to combine this passive filter with active integration (L; R_1; C_2; A_1) and current feedback (R_3) to the negative input of A_1. With proper design of the feedback loop around amplifier A_1, the impedance Z_s (with reference to ground) of this common summing point (S) is kept very much lower than the value of R_1. The overall function of this circuit arrangement is the amplification of the current×time area (charge) of the input pulse, with very good linearity over the entire input frequency spectrum, i.e. accurately integrating the micro structure of the input signal. The output signal is a pulse of about 2 μs duration. It has a completely different waveform than the input signal, but the voltage×time area is strictly proportional to the charge of the bunch signal at the input.

The input impedance Z_{in} of the charge amplifier should match the impedance of the input cable (50 Ω). The reactive component (jωL) has therefore to be compensated. This is done with capacitor C, itself connected via a 50 Ω impedance (R_2) to ground. The equivalent circuit of the charge amplifier input is now:



$$Z_{in} = \frac{j\omega L + R_1 + Z_S - j\frac{1}{\omega C} + R_2}{\left(j\omega L + R_1 + Z_S\right)\left(R2 - j\frac{1}{\omega C}\right)}$$

$j = \sqrt{-1}$ $\quad \omega = 2\pi f$ $\quad f$ = frequency

for: $Z_S \ll R_1$ and $\sqrt{\frac{L}{C}} = R_1 = R_2 = 50\ \Omega$

$\longrightarrow Z_{in} = 50\ \Omega$

Capacitor C has still another function: It serves to couple a test signal (calibration charge) to the input of the charge amplifier. The 50 Ω attenuator allows selection of the calibration charge in 4 steps of 20 dB (1 pC to 1 nC, jumper selected). Providing a calibration mode in this way avoids switching elements directly at the amplifier input or special calibration cables to the sensor. This eliminates also another well known risk, i.e.bringing extra noise from external sources via the calibration circuit to the amplifier input.

Another functional block in the analog signal processing chain is the Bunch Signal Processor (BSP)[6, 7]. This is a dual window integrator which measures the difference between 2 successive samples, the first one being the bunch signal and the second one the baseline reference immediately afterwards. The measurement is repeated for every revolution of the beam in HERA.

Beam current sensors

The beam current sensors for both systems (PCT and BCM) are toroids, placed around the vacuum chamber and mounted in a special beam current transformer assembly [8]. There are 4 independent units (for comparison and redundancy) which are installed in the warm sections of the HERA proton ring. The magnetic field, concentric to the beam, penetrates into this assembly through a ceramic gap in the vacuum chamber. Special care in the design of the chamber elements maintains a low impedance environment for the rf-stucture of the beam and avoids higher order mode losses. Other features of the transformer assembly are multiple magnetic shields, bake out heaters for the UHV vacuum chamber and air cooling to prevent excessive heating of the toroidal transformer cores, which use a temperature sensitive amorphous alloy.

Results of measurements

The resolution of the the DC beam current monitor system (PCT) is limited by noise and zero drift. To measure the resolution under actual operating conditions, PCT readings are recorded without circulating beam in the HERA proton ring.

The monitor control system takes at present one PCT reading per second and stores every 2nd reading in a long term memory for archiving purposes. A data file which includes the beginning of a 2-day shut down, was selected and loaded for evaluation into an Excel spreadsheet. The data (33 000 individual measurements) was formatted in 30 columns by 1100 rows (minutes) to obtain the information which is shown in Fig. 3 and Fig. 4.

The zero drift is mainly a function of temperature. The temperature coefficient ($< 5\ \mu A/^\circ C$) depends on the PCT sensor, not on local electronics. It is planned to incorporate in the future a temperature gauge in the PCT sensor assembly and use it to correct the PCT readings in the local control computer (Fig.1). The limit of resolution is the low frequency noise of the PCT. This noise is less than $0.8\ \mu A_{rms}$ or 0.0004% of FS) for an (arbitrary chosen) sample interval of 60 seconds (Fig. 4).

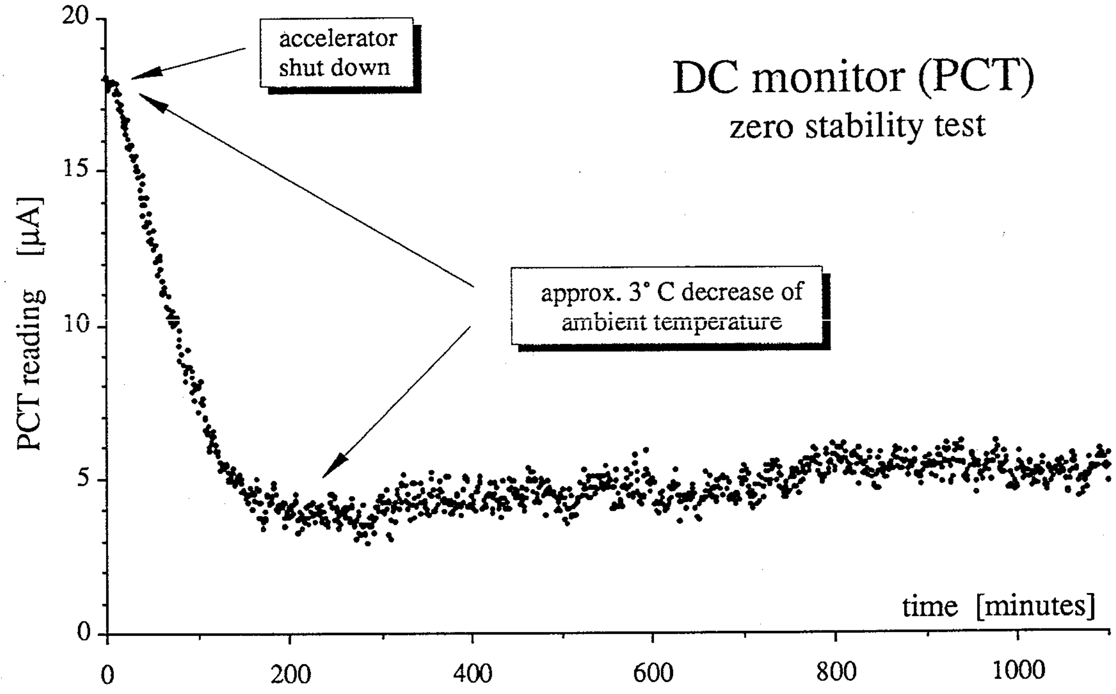


Fig. 3 HERA p DC Beam Current Monitor (PCT - full scale range 200 mA): Zero stability test. Each of the 1100 data points is the average of 30 individual readings, taken at 2 seconds interval.

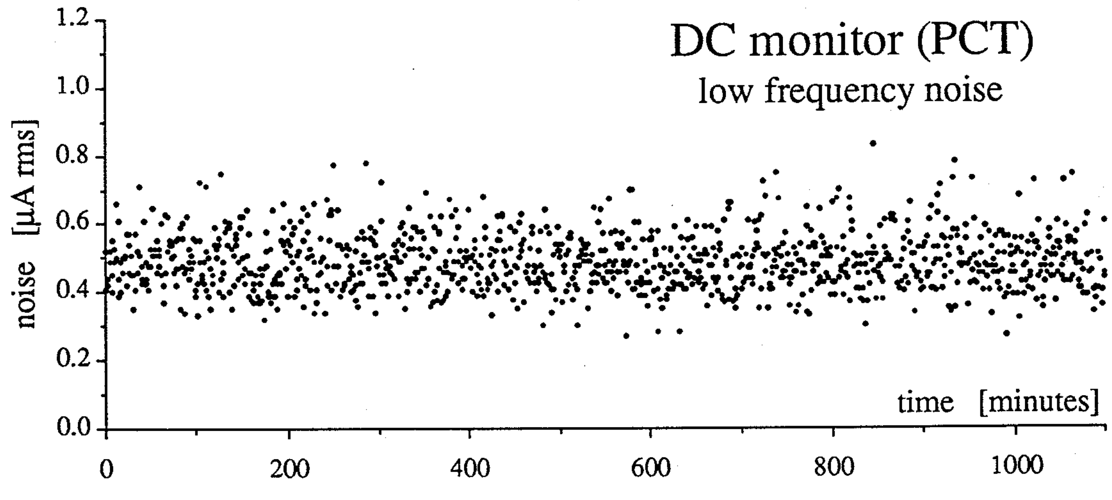


Fig. 4 HERA p DC Beam Current Monitor (PCT): Low frequency noise test. Each data point is the standard deviation σ of 30 individual readings, taken at 2 seconds interval.

A similar data analysis has been made for the Bunch Current Monitor (BCM) and the results are presented in Fig 5. and Fig. 6. It should be noted that the graphs Fig. 3 to 6 use the data files of the same day, which was specially selected to demonstrate the temperature effects. The time scales for all are identical.

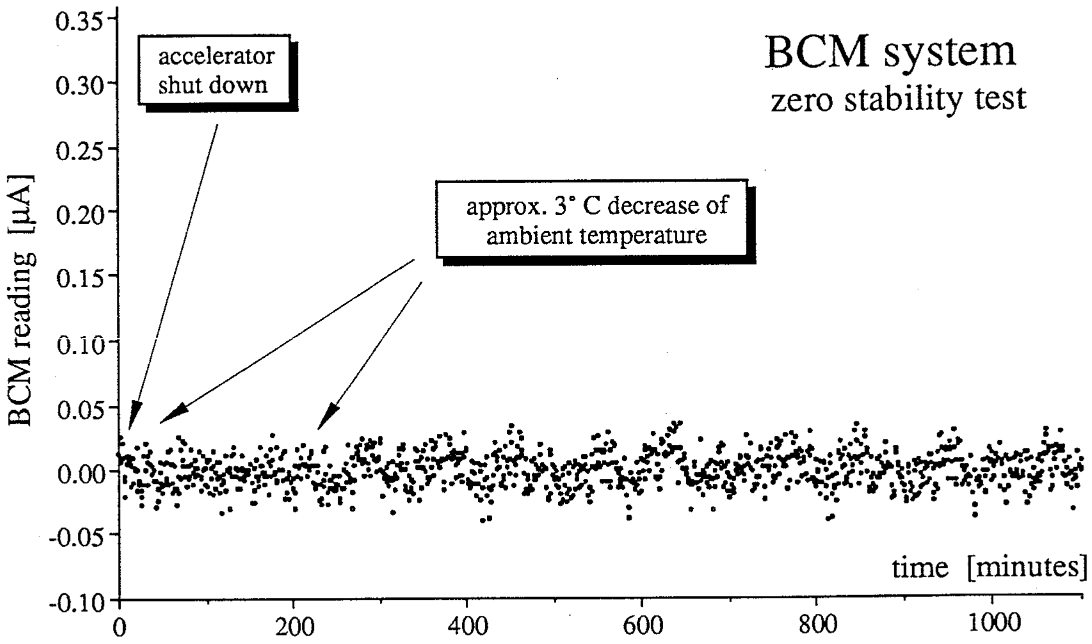


Fig. 5 Bunch Current Monitor (BCM): Zero stability test (full scale range 5 mA). Each of the 1100 data points is the average of 30 individual readings, taken at 2 seconds interval.

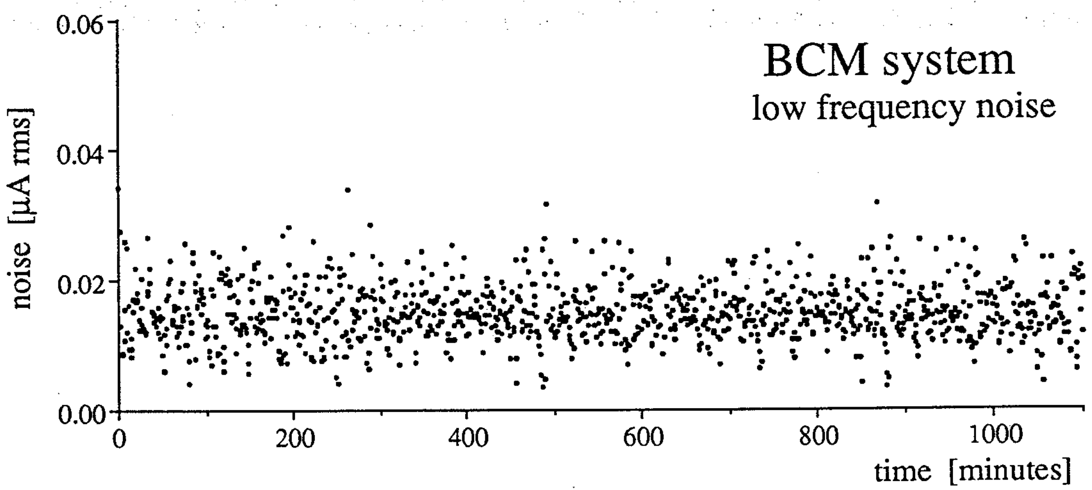


Fig.6 Bunch Current Monitor (BCM). Measurement of low frequency noise. Each data point is the standard deviation σ of 30 individual readings, taken at 2 seconds interval.

The resolution of the BCM should ideally only be limited by the noise of the charge amplifier. Considering that the limit of resolution corresponds to signal levels below 1 µV, it would be desirable to install the amplifier very close to the Integrating Current Transformer (ICT) in the ring tunnel. For reasons of simplified access during these first tests, this charge amplifier was instead installed in the equipment room at the end of a 180 m long cable run. It is not surprising, under these circumstances, that the contribution of noise collected from other sources (harmonics of mains frequency and pulses of different origins) was almost an order of magnitude higher than the amplifier noise itself. This leaves plenty of margin for future improvements!

The ICT current sensor has no temperature drift. The resolution of the BCM system under test is about 0.03 μA_{rms} or about a factor of 25 better than the resolution obtained with the DC Current Monitor. The peak to peak excursions of individual readings (not visible in Fig. 5. and Fig. 6.) are typically less than 0.2 μA_{pp}.

The BCM has a number of limitations: It can only be used when the proton ring is partially filled (1 - 10 bunches in a sampling window of 2 µs). The calibration factor of the digitized output signal (absolute calibration) depends on the setting of external timing and the number and position of bunches inside the sampling window.

The practical use of the BCM is illustrated in Fig. 7. This graph was prepared off line, using the actual data of a machine development run (software for the operational system not completed). This view with an expanded current scale has many advantages over the conventional lifetime plot. Interpretation is much easier, especially concerning the presence of noise. Any change in the trend of the current decay is quickly recognized. The approximate lifetime (rounded value) of the beam should be displayed on request as a dashed reference line.

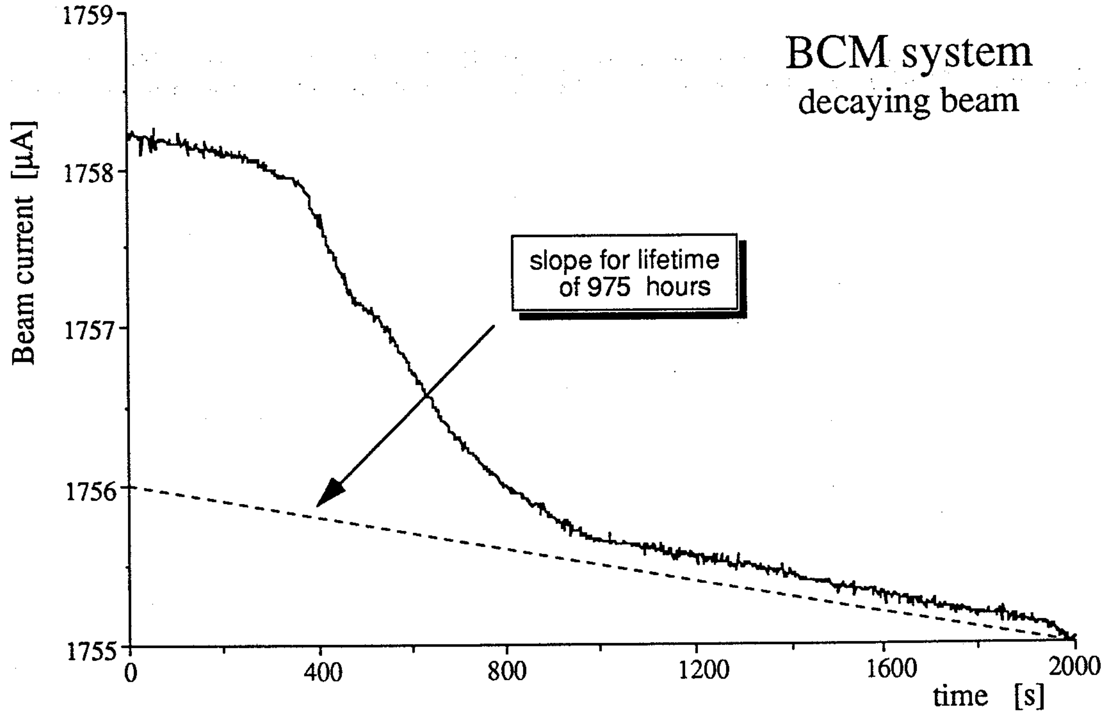


Fig.7 Bunch Current Monitor (BCM): High resolution recording of decaying beam (10 bunches) in the HERA proton ring (full scale range 5 mA) The visible part of the expanded vertical scale corresponds to only 0.24 % of the beam current value. Residual noise on trace is caused essentially by external noise sources

Summary

Description of two different systems to measure the average value of beam current in the HERA proton ring:

The Parametric Current Transformer (PCT) measures the total circulating beam, independent of the bunch structure (d.c. - 100 kHz frequency range). The resolution is 0.8 μA_{rms} (0.0004% of FS range) and the absolute error below 0.1%.

The Bunch Current Monitor (BCM) is a specialized system, to be used when the ring is only partially filled (1 -10 bunches). The resolution (< 0.03 μA_{rms}) is about a factor of 25 better as compared to the PCT, but calibration depends on external timing and the number and position of the bunches in a 2 μs integration window.

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