MEASURING BUNCH INTENSITY, BEAM LOSS AND BUNCH LIFETIME IN LEP

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Abstract: Precision measurement of the beam current in LEP is based on several new concepts. Many of the known defects of earlier systems have now been eliminated at their source. Circulating electron or positron bunches in LEP have rms durations in the range of 30 to 100 picoseconds. The electric charge of each bunch is measured with the passive Integrating Beam Current Transformer. This is a new type of magnetic sensor which uses 2 toroidal cores (amorphous magnetic alloy) in a very special combination. It features exceptionally low core losses and has therefore a very stable and well defined transfer function (calibration factor). The output signal is practically independent of temperature, beam orbit position and bunch length variations. The electric charge (number of leptons) and the beam loss rate is measured separately for each circulating bunch. There are 8 parallel analogue signal processing channels and each is active only during the passage of one selected bunch. Signal processing is performed in the following way: The sensor signal is integrated during a narrow time slot corresponding to the passage of the bunch. The base line level of the sensor signal is integrated during a second time slot of identical duration and subsequently subtracted from the first result. Fast and precise analogue gating functions are obtained by using several cascaded DMOS switching transistors and staggered transition timing. This is a powerful method to restore the dc level of the transformer signal and to obtain the high resolution over a large dynamic range. An additional feature is efficient cancellation of the noise originating from the electronic amplifiers as well as from other external sources.

Introduction

The LEP collider has a circumference of 26.7 km. The 2 colliding beams in this machine are at present limited to 4 bunches of positrons and 4 bunches of electrons which circulate in opposite directions. Each of these bunches has a design intensity of about 4×10^{11} e^+ or e^- with a rms length in the range of 10 to 30 mm. For the purpose of beam instrumentation, these parameters translate into a revolution frequency of 11.24 kHz, a time interval of 22.23 µs between the bunches of the same beam and a rms bunch duration in the range of 30 to 100 picoseconds. Peak values of beam current exceed 1 kA but average only about 3 mA per beam.

Based on operating experience with other colliders and storage rings [2], [4], we can draw up the ideal specifications for the LEP beam intensity monitor as follows: The absolute accuracy of the system should permit to measure the number of particles per bunch during physics runs with an error of less than ± 0.2 %. It should cover a large dynamic range of beam current and should also be able to resolve very small changes in beam intensity (a few parts per million). This would permit accurate measurement of beam lifetime in a short time interval. The measurements should preferably be done simultaneously for each circulating bunch. A beam intensity monitor with these characteristics is essential for efficient every day operation of LEP. It will speed up tuning the collider for optimum performance and help the operators to maintain these conditions during the physics runs. It is also an important diagnostic tool for the accelerator physicists in machine development runs.

Basic design considerations

Meeting the stringent requirements outlined above is a technological challenge. The first task is the selection of a suitable beam current sensor which may be either an electrostatic pick up, a directional coupler, a beam current transformer or an optical detector measuring the synchrotron light. Considering the exceptional performance requirements, each of these devices has certain advantages over the others but also very serious specific limitations. The advantage of a transformer is to measure the current directly by compensating the beam induced magnetic field in a magnetic toroid [3]. If properly designed, there will be no other form of coupling with the beam, which could cause reading errors. But it has as a major disadvantage a response which is too slow and makes the accurate measurement of very short pulsed signals problematic. An original solution was found by developing an integrating current transformer

The required signal processing, i.e. measuring the voltage*time area of the very short pulses over this very large dynamic range, cannot be done with conventional techniques. Thanks to improved characteristics of electronic components and an original circuit concept, much better performance is now possible than in similar applications in the past.

A personal objective was to build a reliable and very simple system, using a minimum of components. The use of a CAD system for electronic design, for analogue/digital simulation and for the layout of printed circuit boards provided major savings in time and cost.

The Integrating Current Transformer

This subject has been covered in a previous paper [4] and is only summarized here briefly. A beam pulse of 30 to 100 ps is too short compared with the rise time ($t_r \geq 1$ ns) of even the fastest current transformer [1], [3]. As we only want to measure the charge (current*time integral) of the bunch, a faithful reproduction of the original shape of bunch signal is not necessary for this instrument. The basic operating principle of the integrating current transformer (ICT) is best explained with the functional schematic below (this is not a mechanical drawing!):

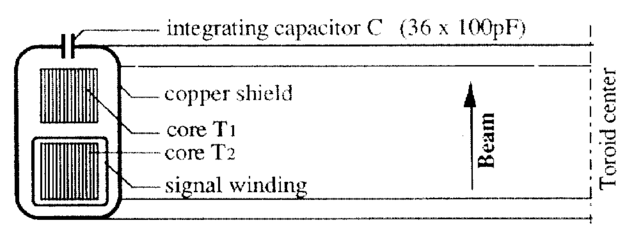

Fig. 1 Functional representation of the integrating current transformer (cross sectional view)

A toroidal shell of copper surrounds 2 magnetic cores (T1 and T2). It forms an electric shield which is not completely closed but leaves a circular gap at the top. There are 36 chip capacitors of 100 pF each soldered at regular intervals across this gap. The primary beam current pulse of the bunch, being a current source, induces an identical value of current in this shield, which is in fact the single turn secondary winding of the ICT. This current charges the integrating capacitor C and the electric charge is practically identical to the original charge of the bunch. The beam current pulse is neutralized by the opposing current in the shield and the magnetic field of the beam does not yet penetrate into the cores. After the passage of the bunch, the current in the secondary winding reverses its direction. The integrating capacitor C discharges now at a much slower rate and couples its charge into the(tertiary signal winding of the core T2. The duration of this discharge is controlled by the inductance due to core T1 and a load capacitance on the signal winding (not shown here).

This arrangement can be considered as a low pass filter for the magnetic field of the very fast primary beam current pulse. The frequency spectrum effectively seen by the magnetic cores is reduced by about 3 orders of magnitude, but the original value of charge is perfectly conserved. The cores (T1 and T2) are made of an amorphous magnetic alloy (Vitrovac 6025, Vacuumschmelze A.G., Hanau,W. Germany) .Excellent magnetic characteristics are obtained with a special manufacturing process [4]. Only a small core cross section is required (5 x 5 mm for a diameter of 215 mm). Core losses are almost negligible, thanks to the quality of the material and to the low operating frequency. The output signal of the ICT is free from overshoot and ringing and has a very narrow frequency spectrum. The shape of this signal is independent of the amplitude and constant for bunch durations below 500 ps.

The ICT is a linear integrator for the entire frequency spectrum of the beam current signal. It has a very stable calibration factor (for charge) which corresponds almost exactly to the turns ratio of the signal winding on core T2. Errors due to the position of the beam in the open aperture, to ambient temperature and to bunch length variations are so small, that they are difficult to measure.

The bunch current monitor system

This system needs only passive elements in the machine tunnel: The beam current sensor ICT and a cable adaptor.are mounted on the LEP vacuum chamber. The cable adaptor consists essentially of a common mode suppression transformer to permit a clean transition between the symmetrical output of the ICT and the asymmetrical coaxial transmission line. It may optionally also contain some filters and reactive elements to compensate matching errors in respect of the 50 Ω characteristic impedance of the cable. A low loss coaxial cable, 50 to 250 m long, transmits the signal to the processing electronics.

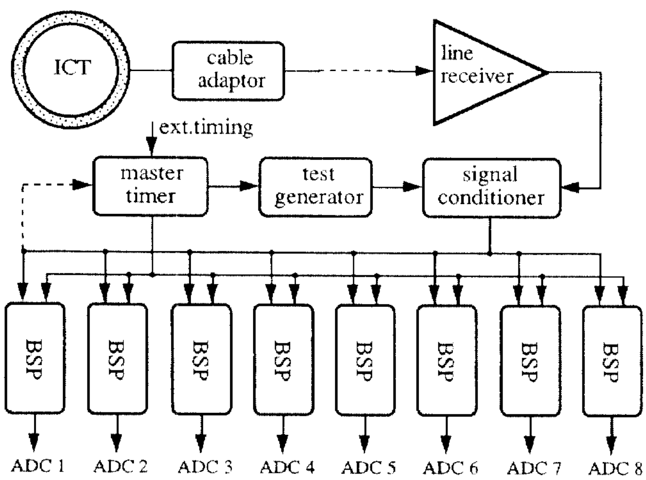

Fig.2 Simplified block diagram of the Bunch Intensity Monitor

The line receiver has the correct line termination impedance and contains another common mode suppression transformer to reduce interference from external sources. It supplies the ICT signal referenced to the local ground. The signal conditioner contains filters and amplifiers with 2 gain ranges. It matches the signal gain to the dynamic range of the the signal processors. Line drivers with a low source impedance feed the 8 bunch signal processors (BSP).

All bunch signal processors receive the same input signal. Each of them is synchronized with a specific timing pulse to one of the 8 circulating bunches in LEP. They integrate the electric charge of each bunch for every revolution of the beams in LEP. The dc signal output interfaces via an ADC [5] to the LEP control system.

A test generator provides a well defined and stable calibration pulse of identical electric charge for each of the 8 BSP channels. This facilitates the testing of all functions of the monitor without beam and the normalisation of the signal gain of all channels. The absolute value of this calibration pulse has to be determined in a special calibration run, using test beams in LEP. The readings for the different bunches are compared with the LEP dc beam current monitor, which is the reference for absolute calibration of beam intensity. [4],[5].

The Bunch signal processor

The bunch signal processor (BSP - Fig. 3) determines to a great extent the dynamic range and the resolution of the intensity monitor. Great care has been taken in designing this circuit for optimum performance. Most of the fast analogue circuitry uses discrete transistors ($f_t \geq 5$ GHz) and fast DMOS switches($t_s \leq 1$ ns) in a surface mount technology (SMT). The fast buffer amplifiers are good examples for showing the performance possible with this technique. Slew rate errors (which would cause nonlinearity) and noise are much smaller than with the best available integrated circuits.

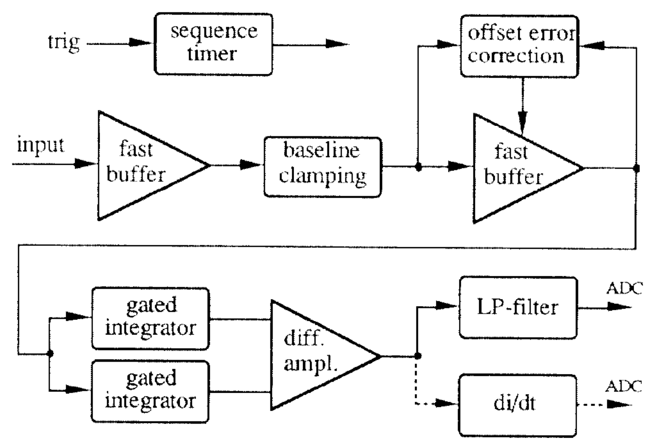

Fig. 3 Simplified block diagram of bunch signal processor

The sequence timer creates 3 identical time intervals in cascade after an external trigger event. The interval can be set to any required value within the limits of 20 ns and 100 µs. The second and the third time interval is used to gate the input signal in 2 independent integrator channels. The first channel integrates the portion of the signal containing the selected bunch pulse and the second channel samples in the same way the baseline immediately afterwards.The result is subtracted from the output of the the first channel. The output of the differential amplifier is therefore proportional to the charge of the bunch signal (voltage*time area). The dc reference level of the signal, which was lost by the transformer, is restored again. The sequence repeats on every revolution of the beams in LEP. The output passes an anti aliasing filter (LP) before being sampled by an ADC. In addition, very small beam decay rates for time intervals ≥ 1 s are resolved with an analogue differentiator circuit (di/dt).

The outstanding feature of this particular combination of sampling integrators is a high degree of noise suppression. All signals which do not correlate in frequency <u>and</u> in time with the sampling windows are rejected. This is true for the amplifier noise and the general interference background, which is so typical for an accelerator environment.This feature satisfies a first condition for obtaining a large dynamic range and high resolution.

The gated integrator

A primary design consideration was to minimize noise and zero drift of the gated integrator. The first step is to select a low noise operational amplifier with a very small bias current. Current noise at the amplifier input is the predominant noise source in an integrator. The noise current correlates to the bias current. Trying now, without any special precautions, to connect a fast analogue gate to the input of this amplifier is likely to increase the leakage current and therefore the noise by orders of magnitude. The simplified circuit diagram in Fig. 4 shows a way to built a nearly perfect gated integrator:

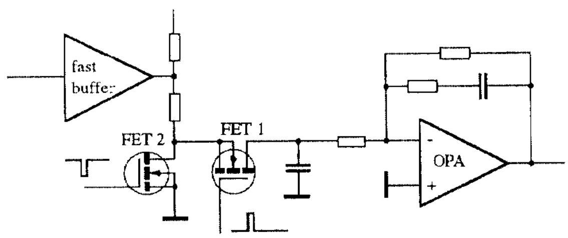

Fig. 4 Gated integrator

In the nonconducting state, the leakage current at the drain of the DMOS transistor FET 1 (depletion mode MOSFET), can be as much as 1 nA. It should ideally be lower than the bias current (10 pA) at the input of the operational amplifier OPA. This can be achieved by keeping source, gate and drain of FET 1 exactly at same (ground) potential.

These conditions are established by using a second DMOS transistor (FET 2) with a complementary gate drive signal as a shunt switch and still another as a baseline clamp, earlier in the signal path and not shown in this diagram. The gate drive signals to these cascaded switching transistors are phased in such a way, that the charge injection from the gate drives is a minimum. Both gated integrator channels are built exactly identical and all dynamic errors introduced by the analogue gates should cancel.

The Bunch signal processor (BSP) has a dynamic range of at least 10^5 and there is still a margin for further improvements.

Mechanical transformer support and vacuum chamber

The mechanical support structure of the beam current transformers in the LEP beam line has to respect a certain number of conditions to assure the required performance of the measurement system. Precaution must also be taken not to cause critical interactions with the circulating beam which could impair the performance of LEP. The basic concept of the mechanical design is a separation of the different functions, using specific elements and structures in successive layers, concentric to the beam. Mounting and dismounting the current sensors is very simple in comparison with earlier designs.

The innermost beam pipe consists of 2 pieces of similar length, each attached to the corresponding vacuum flange. They are separated from each other by a gap of 2 mm width at the center of the unit. This gap is necessary to allow the magnetic field of the beam to pass to the outside. The (inner) elliptical aperture is the same as the standard LEP vacuum chamber.

The elliptical beam pipe is surrounded with a cylindrical vacuum tube in stainless steel. Heating elements and thermocouples for bake out at 150°C are provided.

The following layers are the thermal insulation and a cylindrical water cooled thermal shield (copper). This is also the support for the toroidal beam current transformers. Different sensors belonging to the three independent beam current monitoring systems (dc, bunch intensity and single turn) share the same housing. Each of this sensors has its own electric shields which are isolated from each other and from local ground. Undesirable cavity resonances are damped with two additional toroidal cores (Vitrovac 6025, without windings).

Four solid mounting bars (stainless steel) keep the two vacuum flanges of the assembly at a well defined distance and serve as attachment points for the suspension of the whole unit as well as the support of the three concentric µ-metal shielding tubes.

The transformer unit is completely surrounded with an electric shield in copper, mounted over both vacuum flanges. This has also the function of a by-pass for all currents propagating along the vacuum chamber.

Performance as a Bunch intensity monitor in LEP.

Two complete systems for bunch intensity monitoring are installed in LEP. A special paper [5] reports on digital signal processing and performance. Each of the 8 channels (one per bunch) has a full scale range of 2.5 mA (averaged for 1 complete revolution). The resolution is at present 10 nA or 100 nA, depending on the integration time.

This resolution satisfies the present operational requirements of LEP. Nevertheless different causes which limit the resolution are known and relatively easy to correct. An improved version is under test in the laboratory and will soon be ready for installation.

References

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