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PRECISE INSTRUMENTS FOR BUNCH CHARGE MEASUREMENT

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Abstract

For the pulse charge q injected into a capacitor of a parallel resonance circuit, the oscillation voltage V on a series resistor R is $V = q\omega R\exp(-\pi t/QT)\sin\omega t,\ t \geq \tau$, where ω is the resonance frequency, $Q \gg 1$ is the quality factor and $\tau \ll 2\pi/\omega$ is the pulse length. Of the three parameters, R is known, and ω and Q can be found directly from the signal. The observations above open a possibility of precise bunch charge measurement. We investigate two approaches: a quasi-static resonator as a bunch charge monitor, and a monitor as a novel open-gap pickup in pair with a precise LC integrator circuit. The monitor with integrator has a lower range 10 pC/V and the noise floor about 40 fC as measured on an integrator prototype with a Faraday cup. Several such circuits are in use on the VELA injector at Daresbury Laboratory. Open-gap pickup prototype design is in progress.

INTRODUCTION

In this paper we propose and consider concepts of precise non-intercepting bunch charge monitoring, specifically on modern light sources where shot-to-shot bunch charge variation requirement is quite stringent (rms: LCLS ≤2%, CLARA ≤1% [1]). Providing high resolution and necessary stability, it would be useful to advance with the absolute accuracy as well. With all the targets attained, the new monitor could substitute the Faraday cup whose use at the energy above 10 MeV becomes problematic due to its large dimensions.

We can take the bunch rate range extending from say, 10 Hz, to 1 MHz (as in the light source projects), and the bunch charge range from 1 nC down to 1 pC. The bunch length is typically shorter than 1 ps.

A charge monitor should pick up the total current induced by the propagating bunch in the conductive pipe wall, as the total current doesn't depend on bunch offset from the pipe axis. To get the bunch charge, the total current pulse should be integrated.

We have developed two kinds of charge monitor. One is based on a pickup as a quasi-static resonator, which integrates the wall current at the resonator capacitor that is connected to a transverse gap in the pipe. In another one, an open-gap pickup delivers a current pulse that is integrated in a separate Front-End based again on the idea of integrating by a resonance circuit. The merit of this approach is that the output signal represents the bunch charge through well-specified parameters: the resistance of a lump resistor, along with the output oscillation frequency and quality factor that both can be obtained immediately from the signal. One more merit of the monitors is a low dark current sensitivity due to alternating character of the monitor's output signal.

The quasi-static resonator monitors were used in the past for monitoring bunches in transfer lines of an electron-positron collider. The open-gap pickup is now in the prototyping stage. It is planned to finalise the design and test/use these pickups on VELA/CLARA [1] together with integrating Front-Ends. Several Front-Ends are now in use on the VELA injector with Faraday cups and with a wall current monitor.

Here we describe resonator monitors, discuss a novel monitor, derive the output signal expressions, and analyse the errors and drawbacks.

THE METHOD

Consider a parallel resonance circuit consisting of the capacitance C, and the inductance L in series with the resistance R. For the current pulse $j = q/\tau$ injected into the capacitance, the oscillation voltage V on the resistance for $t \geq \tau$ is:

$$V = q\omega R\left[1 - \frac{\pi}{2Q}\left(\frac{\tau}{T}\right) - \frac{\pi^2}{6}\left(\frac{\tau}{T}\right)^2\right] e^{-\frac{\pi t}{QT}}\sin(\omega t + \xi) \quad (1)$$

where q is the charge, $\tau \ll T$ is the pulse length, ω is the resonance frequency, $T = 2\pi/\omega$, $Q \gg 1$ is the quality factor, $\xi \ll 1$ is some phase. In the expression (1) we omitted $1/8Q^2$ as practically always negligible in comparison to 1. The exact expression contains also two power series in τ/T. Each of them after truncating is presented in (1) by a practically significant term (between square brackets). For $\tau/T = 1/10$, and $Q = 10$, each term is about 1/60.

The expression represents the idea of bunch charge measurement using a resonance circuit with lump elements. The signal (1) is proportional to the bunch charge. Assume that the terms between square brackets are negligible. Then for a known resistance R, sampling the signal and then processing the samples to obtain the voltage, frequency and quality factor, one can find the bunch charge. The required accuracy specifies the sampling/processing precision.

Another merit of the method is low dark current sensitivity. Simulation shows that the oscillating response to a 3.3 μs bunch train with linearly increasing bunch charge (the bunch rate is taken as 3 GHz, $\omega = 2\pi \cdot 15$ MHz, $Q = 50$, see below) is at the train end about 20 times lower than the response (1) to the last bunch if it would be single.

QUASI-STATIC RESONATOR AS A CHARGE MONITOR

The first realisation of the method above is described in [2]. There the resonance circuit is made as a quasi-static resonator built in the vacuum pipe.

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A resonator consists of a toroidal inductive envelope that is connected to a transverse gap in the beam pipe. To have this resonance cavity arrangement quasi-static, a magnetic core is placed in the envelope, and lump capacitors are spread along the gap. The resonance wavelength of such resonator becomes much greater than its characteristic size, the electric and magnetic fields are separated, and the displacement current everywhere beyond the capacitors can be neglected (hence quasi-static). The displacement current through the capacitors practically fully converts to conduction current in the inductive envelope wall. The latter current produces the output signal.

A resonator monitor with a resistive 'wall' is shown in Fig. 1. The resistive wall (marked with 5) is combined from n lump resistors (total resistance R). One of the resistors is replaced with a wire going to the output coaxial connector (8). The resistive wall divides the envelope into two parts: one is the resonator inductor (L, 3) with a core (4), another one, on the resistors' opposite side is a parasitic inductor (L_p, 6, also with a magnetic core, 7). The capacitor C is a section of a low impedance coaxial line (1 and 2).

The resonator's Laplace transform is a polynomial of power 3. The reverse transform as a response to a current pulse $j = q/\tau$ for $t \geq \tau$ is:

$$V = q\omega R \begin{bmatrix} \left(1 - \frac{a\tau}{2} - \frac{\omega^2\tau^2}{24}\right) e^{-at} \sin(\omega t + \varsigma) - \\ - \frac{b}{\omega}(1 + b\tau) e^{-bt} \end{bmatrix} \quad (2)$$

where $\tau \ll 2\pi/\omega$, $Q \gg 1$, $a \sim b \ll \omega$. The numbers ω, a and b are algebraic combinations of C, L, L_p, and R and can be found as numerical solutions of three simultaneous equations. In (2), like in (1), $1/8Q^2$ is omitted, and the series are truncated. The sag (the second term) appears due to parasitic inductor.

The monitor above has $T = 2\pi/\omega = 25$ ns, $Q = 18$ and $R = 1.25\ \Omega$. The sensitivity calculated for the first maximum of the oscillation (2) is 0.28 V/nC.

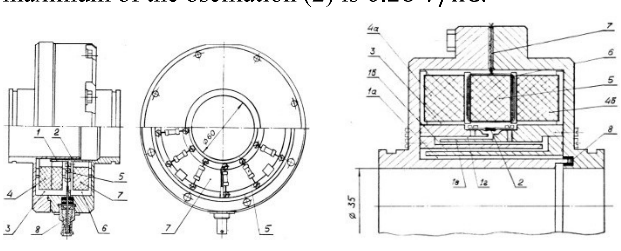

Figure 1: A quasi-static resonator as a charge monitor. Left: a monitor with a resistive 'wall'. Right: a monitor with a transformer.

A monitor with a transformer output is shown in Fig. 1 (right). The inductive envelope is marked by 6, magnetic core (two rings) by 4a and 4b, the capacitive 'wall' is made from capacitors 2. The transformer 5 (the turn number is w) with the output wires 7 is made on one more core. The output expression is similar to (2) with ρ/w instead of R where ρ is the load resistance. The numbers ω, a and b are algebraic combinations of C, L, L_μ, ρ, and L_s as well, where L_μ is the transformer inductance, L_s is the stray inductance. The parameter values are: $T = 160$ ns, $Q = 20$, $\rho = 100\ \Omega$, $w = 10$. The sensitivity is 0.33 V/nC.

This monitor has some merits. First, due to transformer, it is well matched to load and has an optimal signal-to-thermal-noise ratio. Next, the symmetric output opens possibility to use a symmetric transmission cable and achieve good rejection of external noise. Besides, the monitor has a built-in coaxial labyrinth (marked with 1) for suppression of a quasi-static magnetic field in the case when a monitor is close to a pulse transfer line magnet [2].

As for the accuracy, the use of a transformer is a week point as the turn number is an imprecise parameter.

The core material is ferrite. The resonator core permeability should have the cut-off approximately at the monitor resonance frequency. This provides a high quality factor. Both the parasitic inductor core and transformer core can have the permeability as high as available. The sag contribution in this case is minimal.

For quasi-static monitors the condition $\tau \ll 2\pi/\omega = T$ of the expression (2) is practically uncomprehensive. Each gap in Fig. 1 is made as a short coaxial line. In other monitors it might be a radial line with a ceramic insert. The propagation time along any of those lines is typically a fraction of ns. The wave packet induced by a short bunch in the line experiences multiply reflections on its open ends and disperses due to resistive loss. On each passage the packet charges the lump capacitor. Not considering here what the capacitor equivalent circuit is and how the wave propagates there, one can say that a settling time τ_settl that is necessary for conversion of the waves into a quasi-static voltage q/C is significantly bigger than the bunch length τ which leads to a heavily restrictive condition that absorbs the condition $\tau \ll T$:

$$\tau_\text{settl} \ll T. \quad (3)$$

OPEN-GAP PICKUP

Here we propose another variant of charge monitor. It is based on an open-gap pickup that delivers the full bunch charge and can be interpreted as a non-intercepting Faraday cup.

The pickup output is fed into a separate integrator. The function separation allows coordinating of the devices in an optimal way as to achieve the monitor sensitivity and resolution more than ten times higher than those of the resonator monitors above.

Use of an open-gap pickup in a monitor with separate functions allows eliminate the error due to practically unavoidable reflection at the integrator input. A reflection wave comes to the open gap, reflects back and returns to the input. This ensures full charge absorption provided that the multi-reflection settling time $\overline{\tau_\text{settl}}$ is within the integrator range.

An integrator circuit is described in the next section. An open-gap pickup is shown schematically in Fig. 2. The

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circular gap is shielded with a toroidal envelope. Inside it, n parallel circuits are connected to the gap, evenly spread along the circumference. Each circuit consists of a cable connected through the resistor R to the gap opposite edge. With L^* is denoted a partial wall inductance of the connection, the partial gap capacitance is C_g^*. An auxiliary capacitor C is connected to the cable input.

The gap and circuits are by-passed by the envelope. To reduce a wall current leakage into it, a ring magnetic core is placed inside.

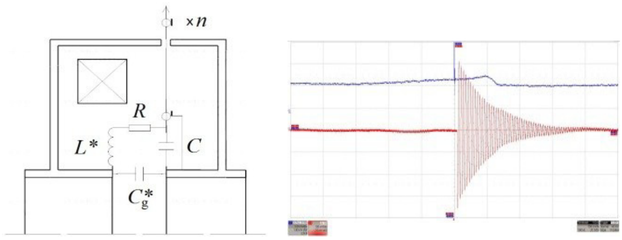

Figure 2: Right: open-gap pickup. Left: integrator signal from WCM.

The partial wall current charges the gap capacitance C_g^*. Further the charge flows through L^*, R to the capacitor C and the cable input. The input pulse has a triangle shape: a smooth front formed by the L^*RC chain, and an exponential fall with $\theta = \rho C$ where ρ is the cable impedance. The pulse area is equal to the partial bunch charge and doesn't depend on the circuit parameters above. They can be set to have a pulse shape optimal for the integrator.

To get full bunch charge, the output pulses of the parallel circuits should be summed up.

FRONT-END INTEGRATOR

We developed an integrator based on a resonance LC circuit. Use of common-base transistor cascade as an effective impedance transformer opened possibility to develop a precise low noise and high sensitivity device.

The integrator basic circuit is shown in Fig. 3. It has n cable inputs (the cable impedance is ρ) combined at the low ($r_E \sim 2\ \Omega$) impedance input of the transistor T1. This input is a point where the open-gap pickup pulses are summed up.

The T1 collector injects the pulse current into the capacitor C. This capacitor and the inductor L that is connected to a low impedance input of the transistor T2 are the resonance circuit. The oscillation current developed in it, is fed into the output resistor R.

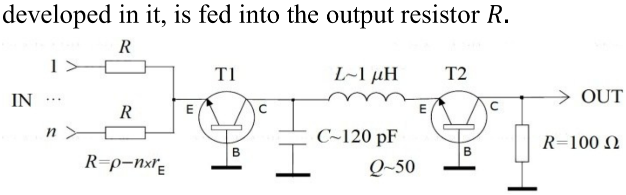

Figure 3: Integrator basic circuit.

The integrator response to a bunch pulse is given by the expression (1) where $\overline{\tau_{settl}}$ should be used instead of τ. For $\omega = 2\pi \cdot 15$ MHz ($C \cong 120$ pF, $L \cong 1$ µH, $Q \cong 50$) and $R = 100\ \Omega$ the sensitivity is 10 V/nC. With an additional output amplifier ($G = 10$, like in the prototype below), the sensitivity rises up to 100 V/nC. The narrow-band noise is about 40 fC rms. The oscillating response to a linearly increasing dark current (for total charge 1 nC) is of the order of the noise above.

The expression (1) doesn't include all errors of the circuit. First, an error is there due to the transistor current gain α is not exactly 1 ($\alpha \cong 1 - 1/\beta$, for $\beta \sim 200$ the error is -0.5%). Second, for a big input signal the transistor nonlinearity should be considered. Note that oscillation current leakage into the transistor output impedance is negligible as the impedance is more than three orders greater than ωL or R.

For a monitor with the resonance frequency 15 MHz the settling time several ns is acceptable ($\overline{\tau_{settl}}/T \sim 1/10$). The pickup pulse rise/fall time of about 1 ns is suitable for the integrator broadband transistors BFR183 ($f_T =$ 8 GHz) that we use in the prototype.

Several single-input prototypes are used on the VELA Injector for integrating bunch pulses from a common WCM (1 Ω impedance) and Faraday cups. A signal from the WCM is shown in Fig. 2 in red. Other trace (blue) is a direct WCM signal. It shows a gradually increasing dark current (total charge is about 0.5 nC) a vertical mark on which is the bunch. The bunch charge is about 150 pC.

SUMMARY

We present a status of bunch charge monitor development in Daresbury Laboratory within the CLARA Project. We discuss the monitoring based on integration of the wall current in a resonance LC circuit. We describe two approaches: a quasi-static resonator built in the vacuum pipe, and a stand-alone LC integrator circuit. We suggest a novel open-gap pickup that in pair with the precise integrator circuit allows advancing in the monitor accuracy. We develop an open-gap pickup prototype and plan to test it on the VELA Injector. Tests of the integrator circuit prototype demonstrated that the monitor sensitivity 0.1 V/pC and a noise floor of tens of fC are achievable.

ACKNOWLEDGMENT

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REFERENCES

[1] J. A. Clarke et al., "CLARA conceptual design report", *JINST* **9** T05001, 2014
[2] A. S. Kalinin, *Charge Particle Beam Diagnostics for Storage Rings and Transfer Lines*, PhD Thesis, BINP, Novosibirsk, 1985 (in Russian)